Overview of recent ALICE results

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Petersburg Nuclear Physics Institute

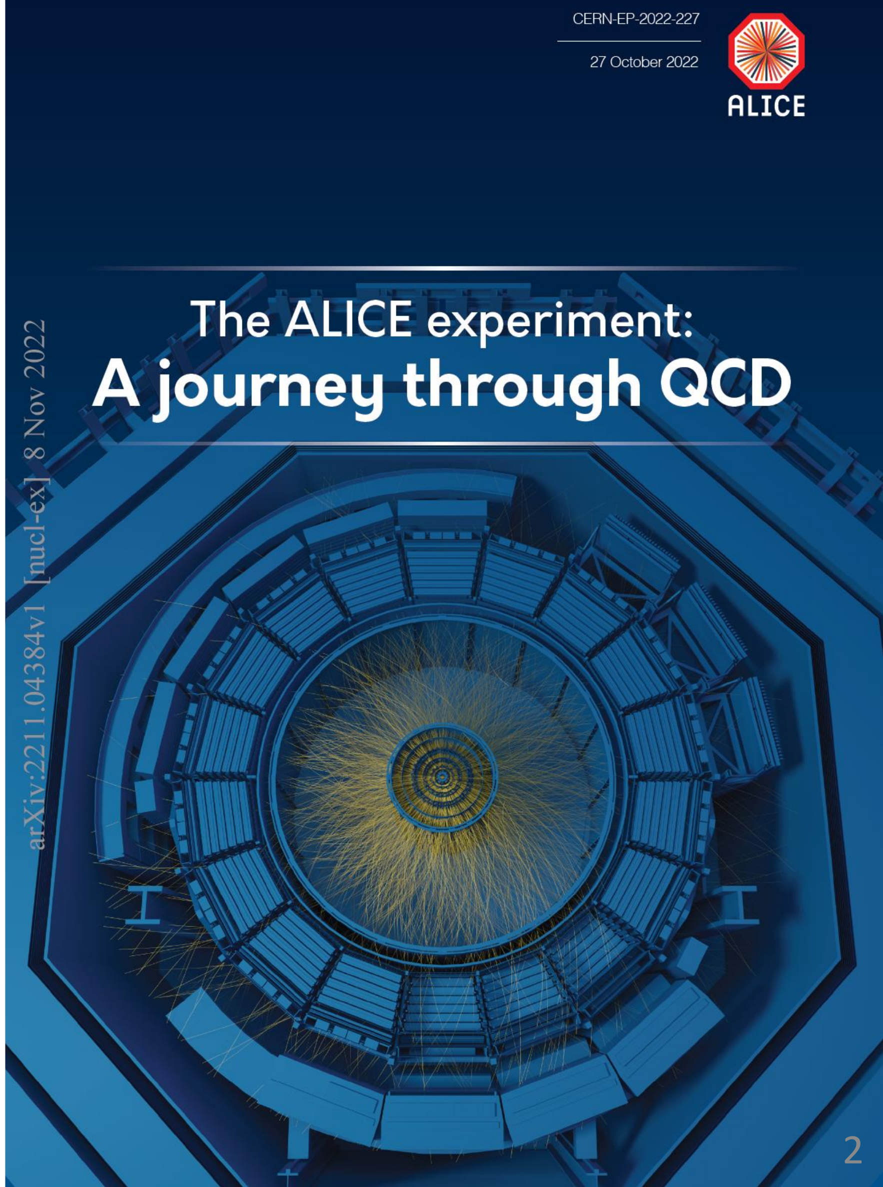
XXXV Intrantional Workshop on High Energy Physics
“From Quarks to Galaxies: Elucidating Dark Sides"
29 November 2023

A journey through QCD

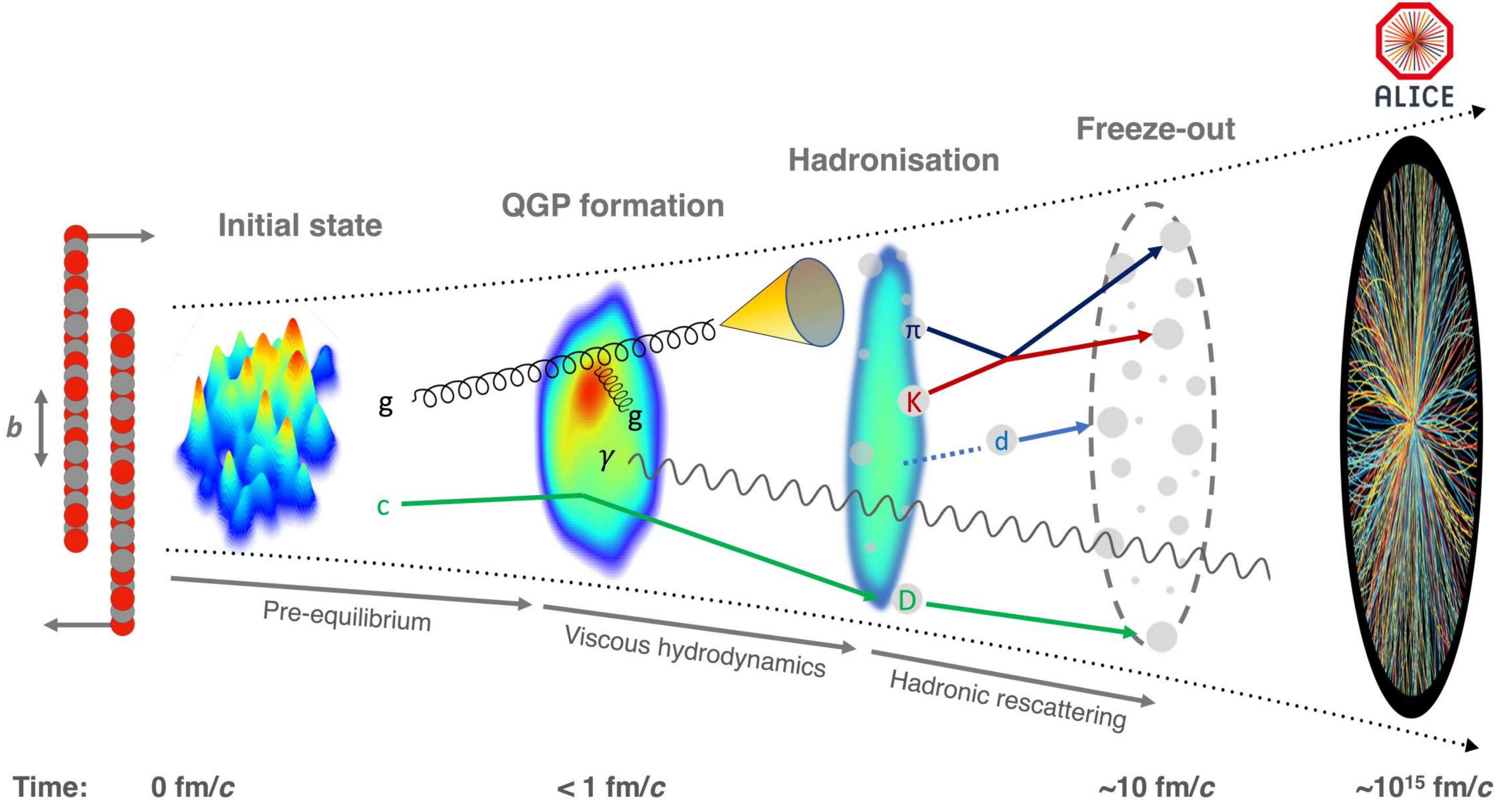
ALICE review of Run 1-2 studies:

- QGP properties in heavy-ion collisions
  - Macroscopic properties
  - Interactions of partons with QGP medium
  - Hadronization
  - Electromagnetic effects
  - Initial state
- QGP-like effects in small systems
- Many other aspects of QCD and beyond

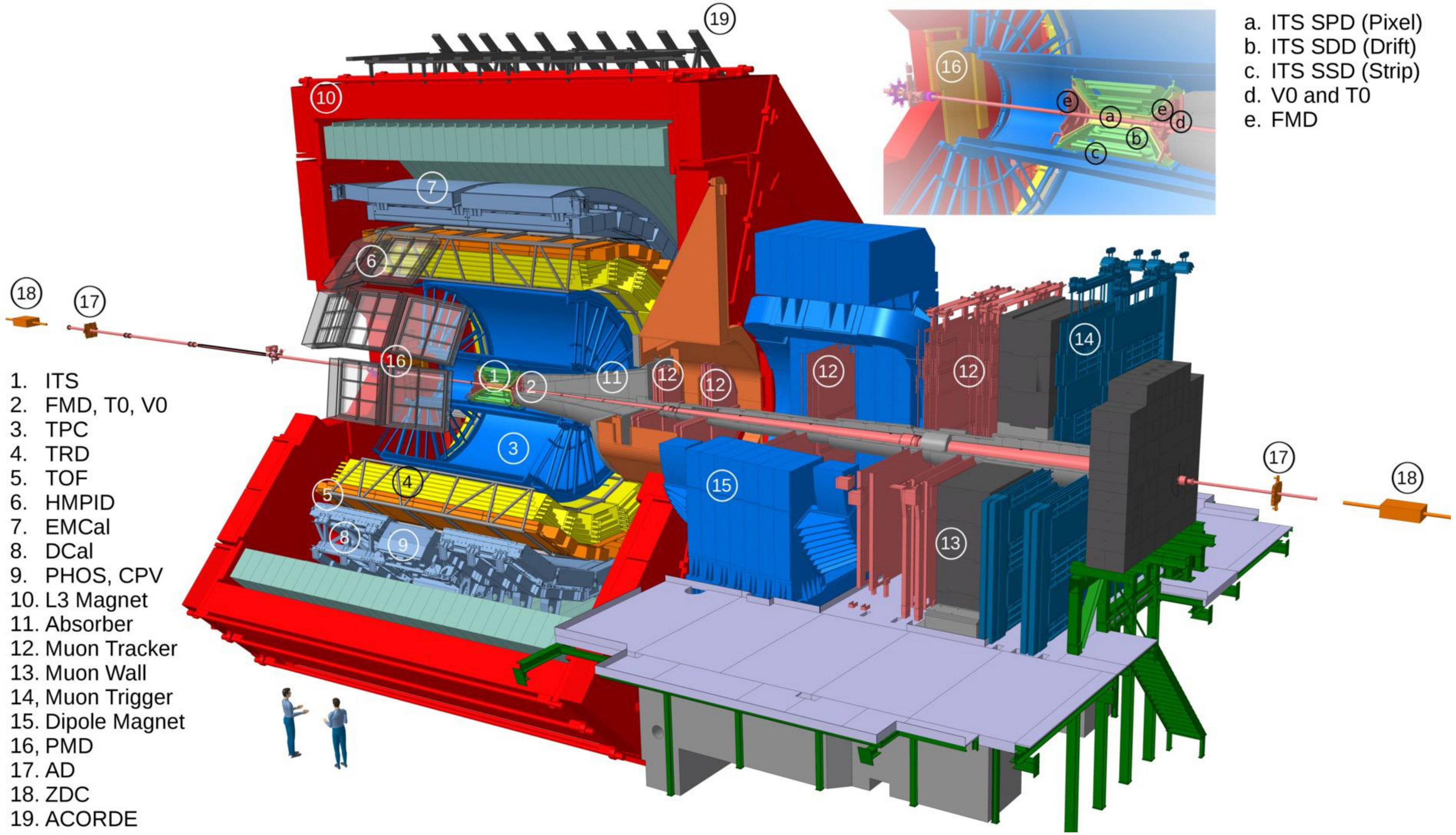
ALICE,arXiv:2211.04384

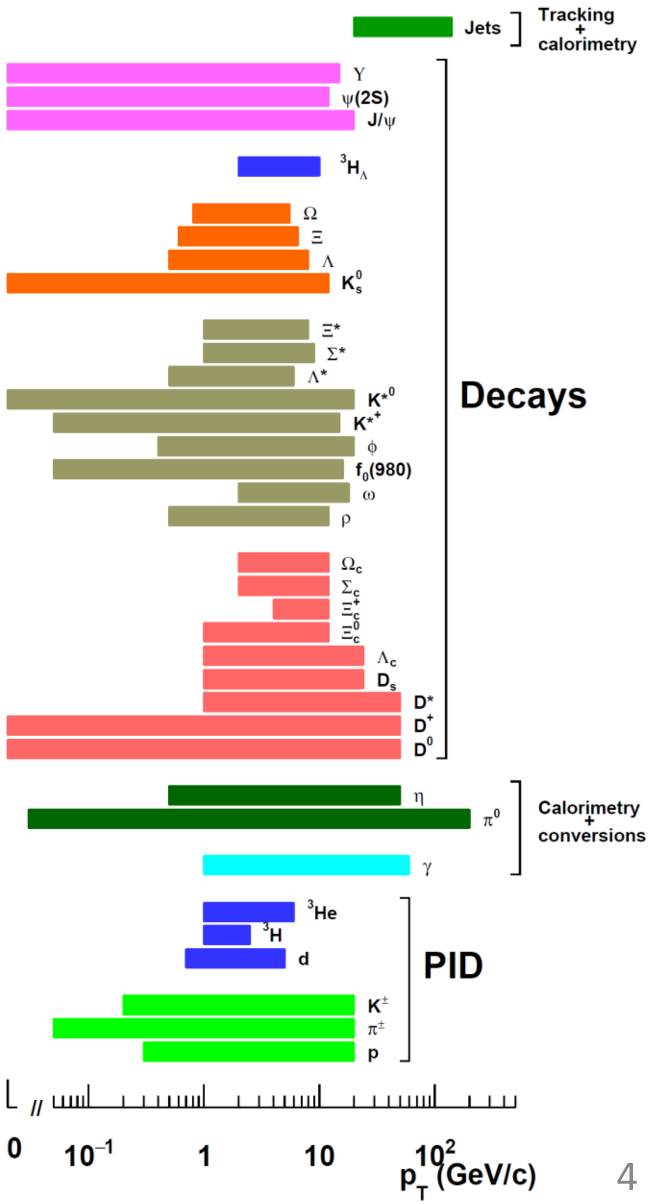


Relativistic heavy-ion collisions



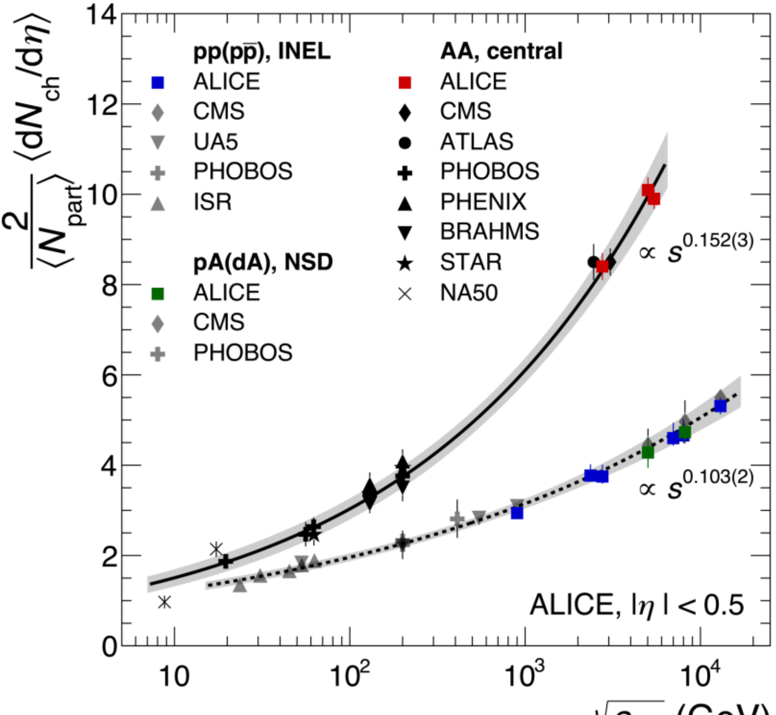
ALICE detector



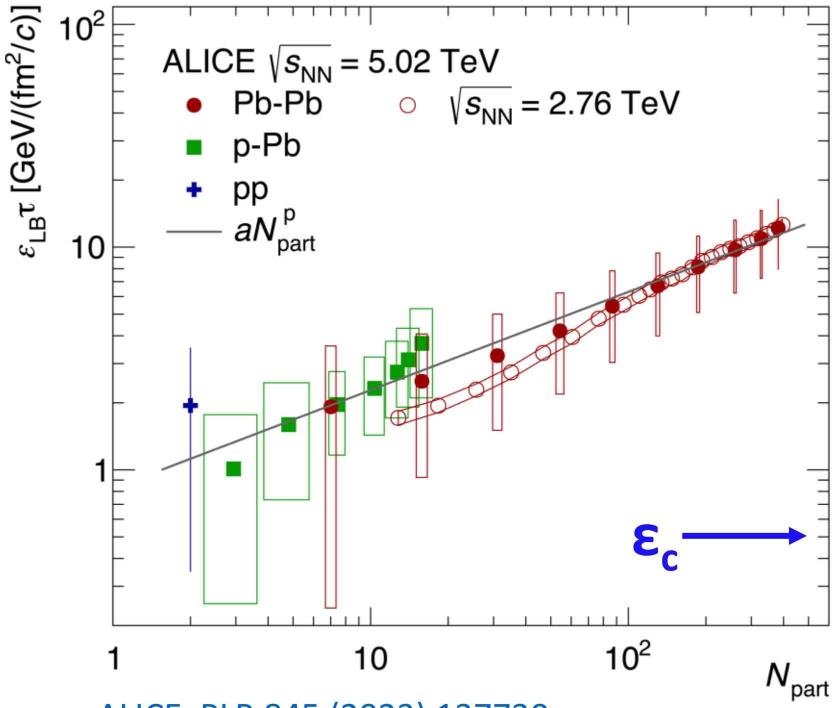


- Broad momentum acceptance
- World leading particle identification
- Precise vertexing

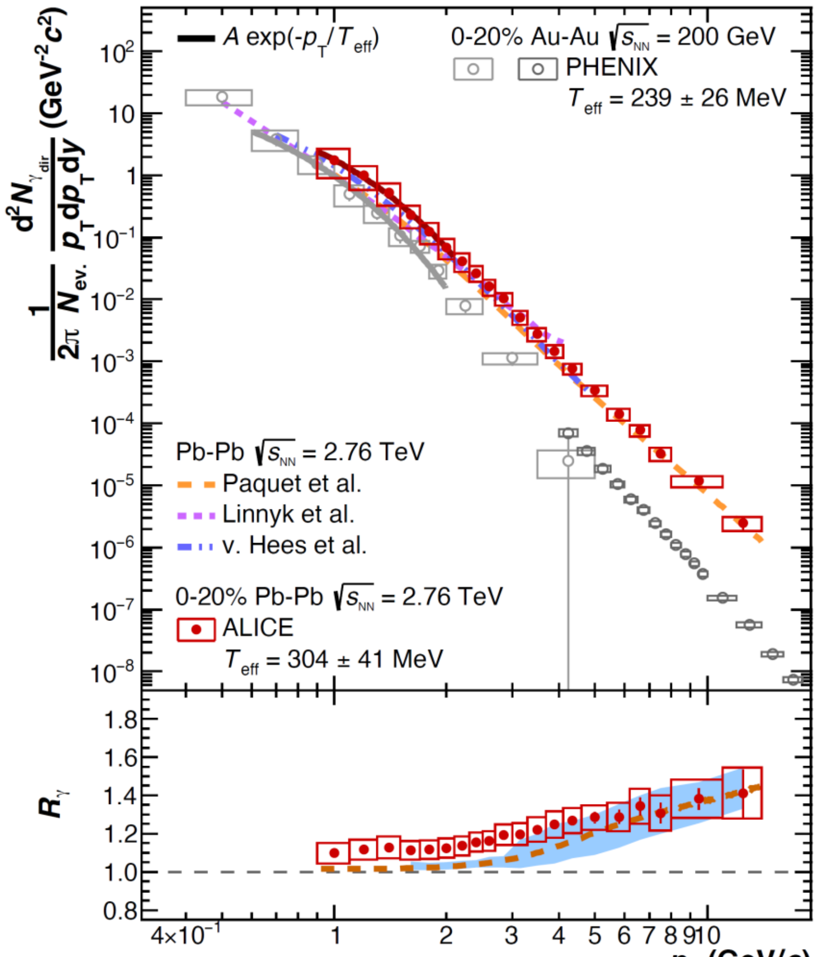
Global properties



ALICE, EPJC 79 (2019) 307



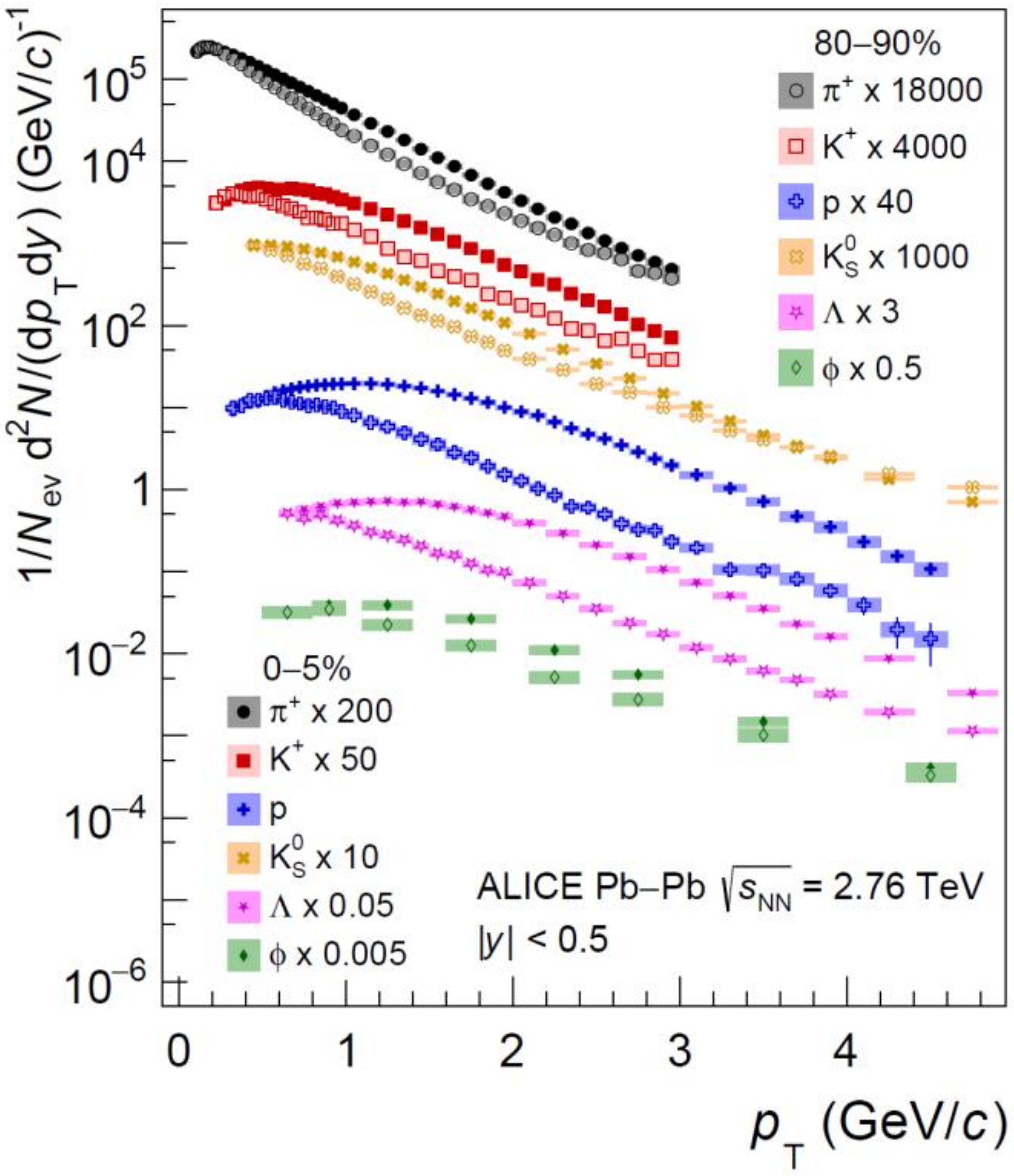
ALICE, PLB 845 (2023) 137730



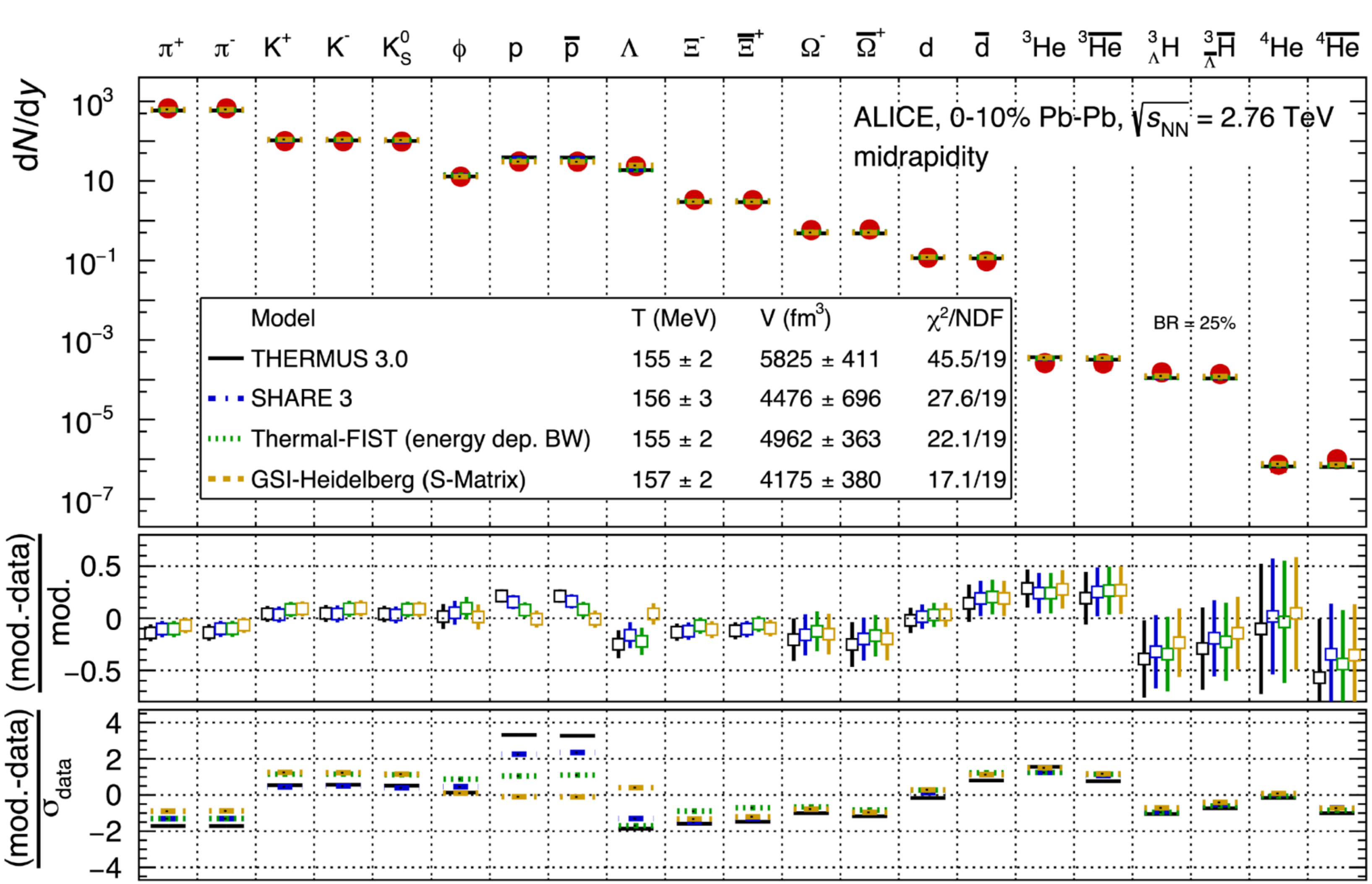
ALICE, PLB 754 (2016) 235

- Charged hadron production per nucleon maximal in Pb-Pb at the LHC
- Initial energy density in central Pb-Pb collisions is 30 times larger than ε_c!
- Effective photon temperature T_{eff} = 304 ± 41 MeV twice larger than T_c ~ 160 MeV

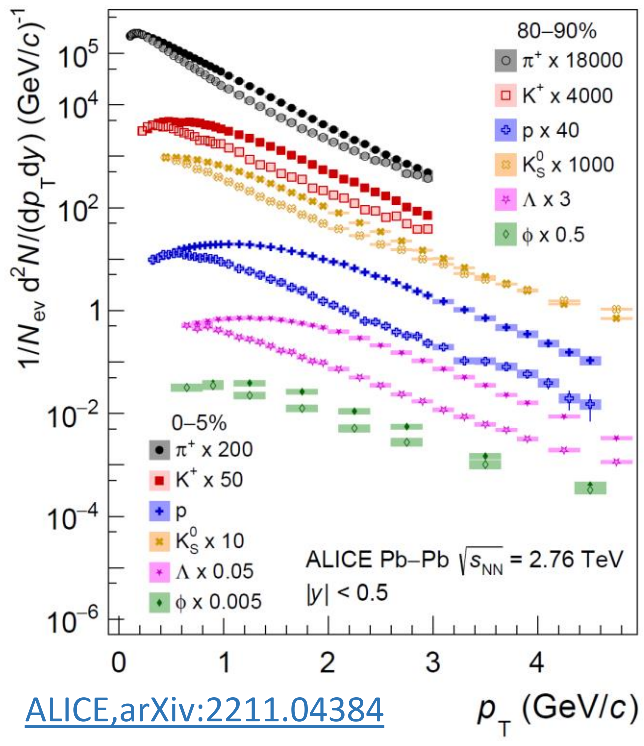
Light flavour spectra



Light flavour spectra



[ALICE,arXiv:2211.04384](https://arxiv.org/abs/2211.04384)

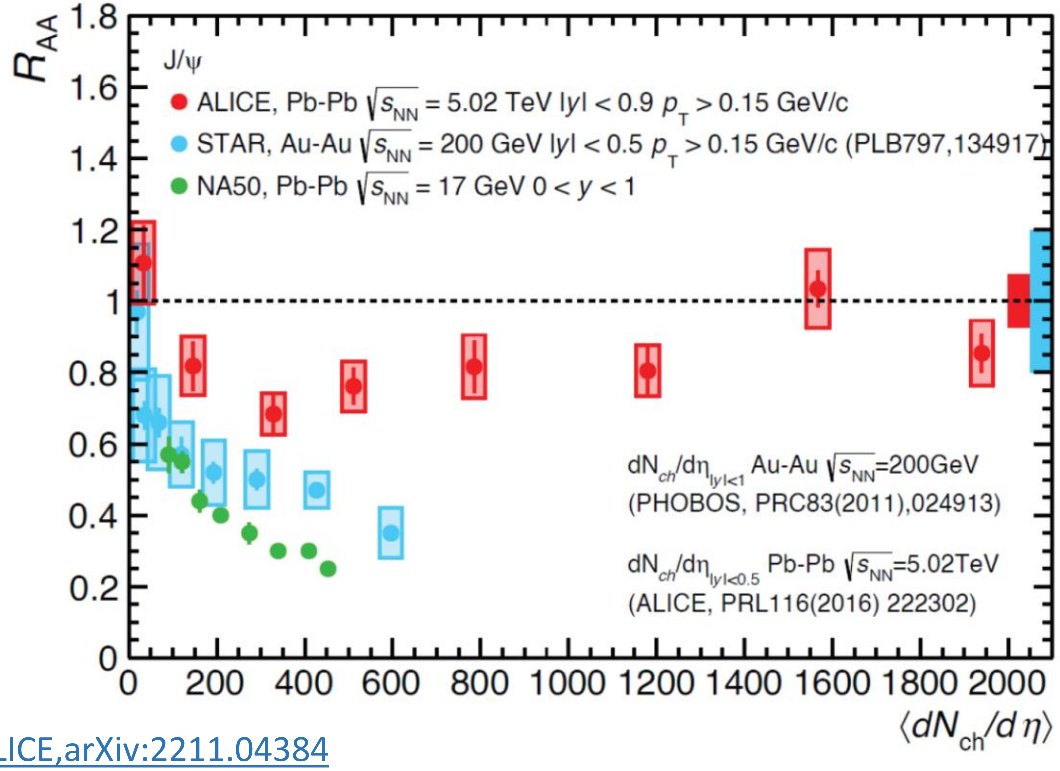


[ALICE,arXiv:2211.04384](https://arxiv.org/abs/2211.04384)

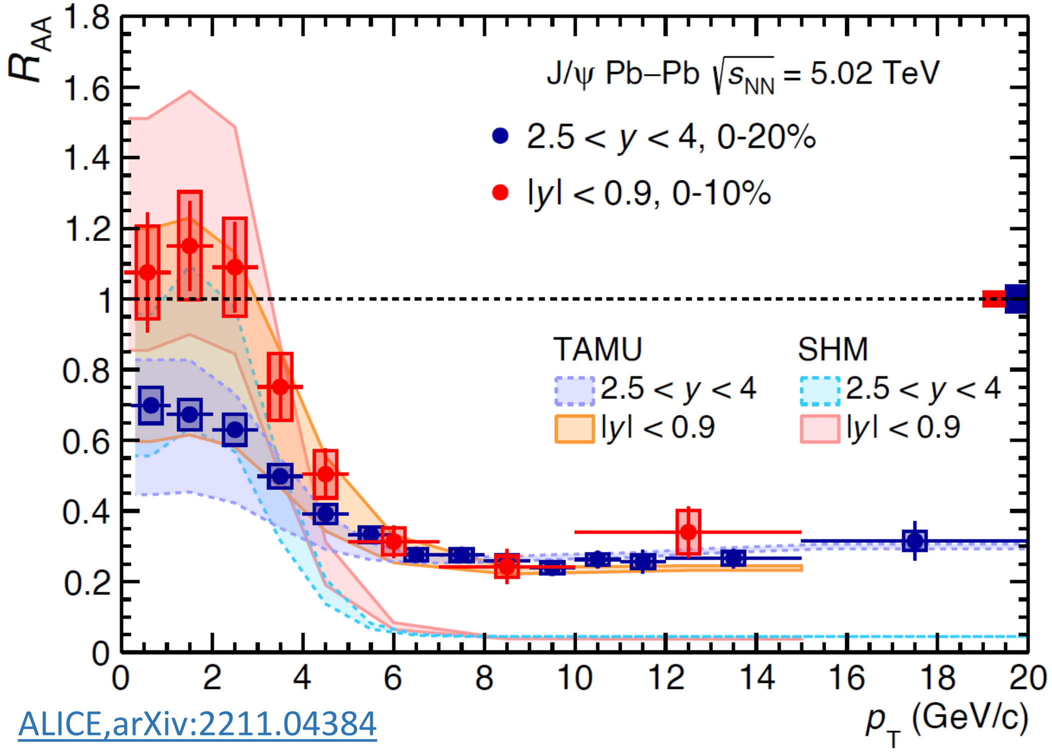
- Hadron yields described by statistical hadronization models over many orders of magnitude
- Chemical equilibrium close to QGP transition temperature

$T_{chem} \approx T_c \approx 156$ MeV

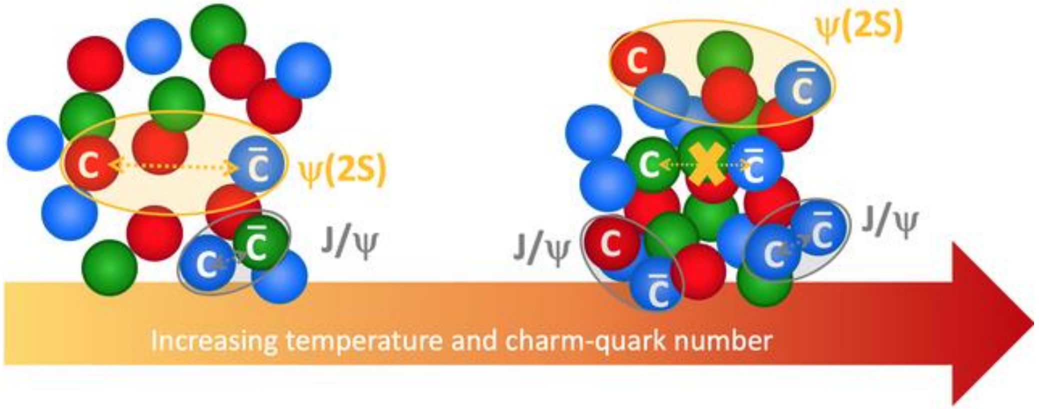
Charmonium melting and regeneration



ALICE,arXiv:2211.04384

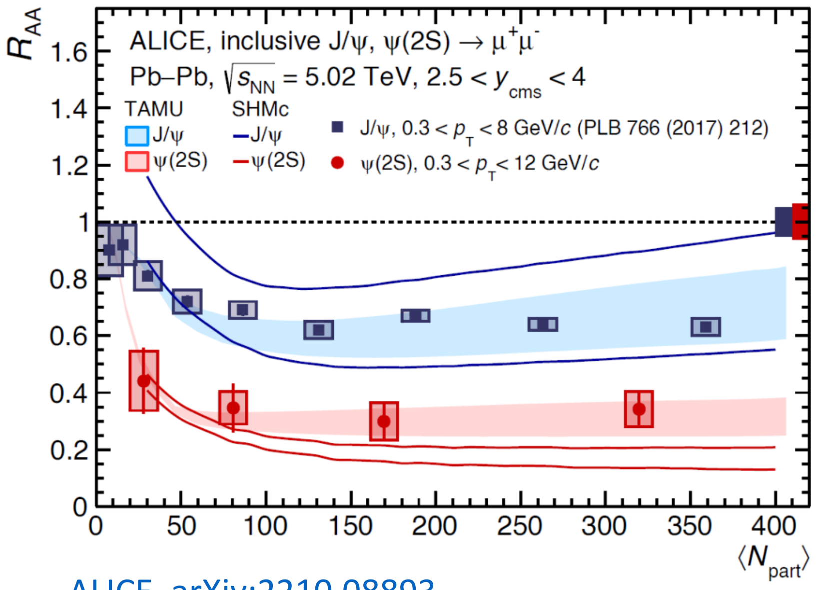


ALICE,arXiv:2211.04384

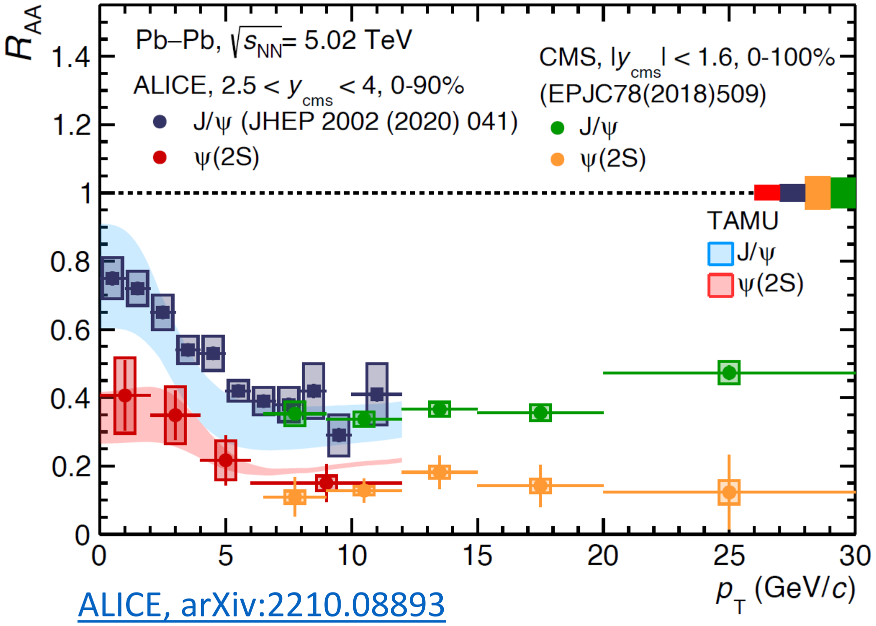


- Interplay of melting and regeneration effects
- Large regeneration effects at the LHC due to much larger charm cross section compared to RHIC/SPS
- Larger regeneration effects at midrapidity and at low p_T

Excited quarkonium states



[ALICE, arXiv:2210.08893](https://arxiv.org/abs/2210.08893)



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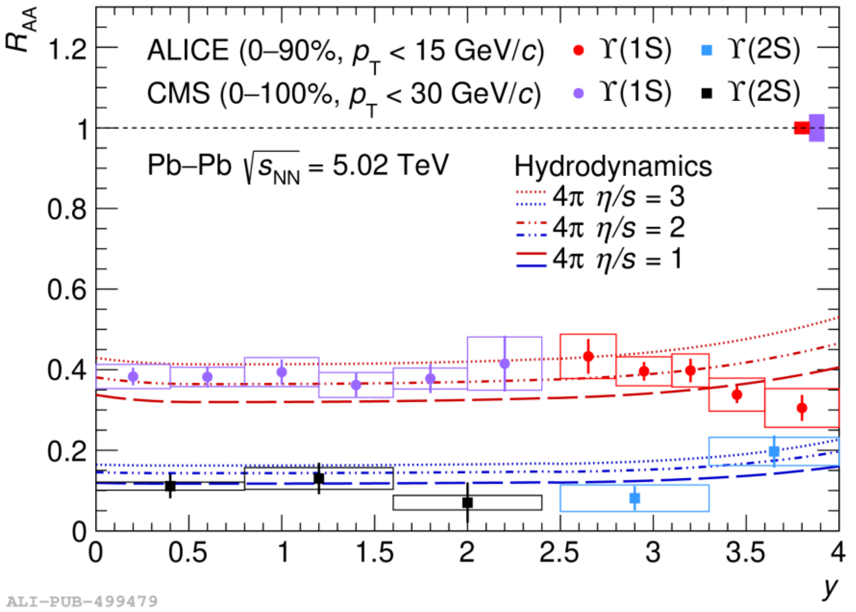
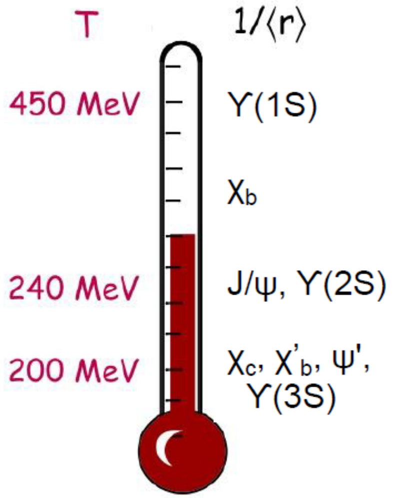
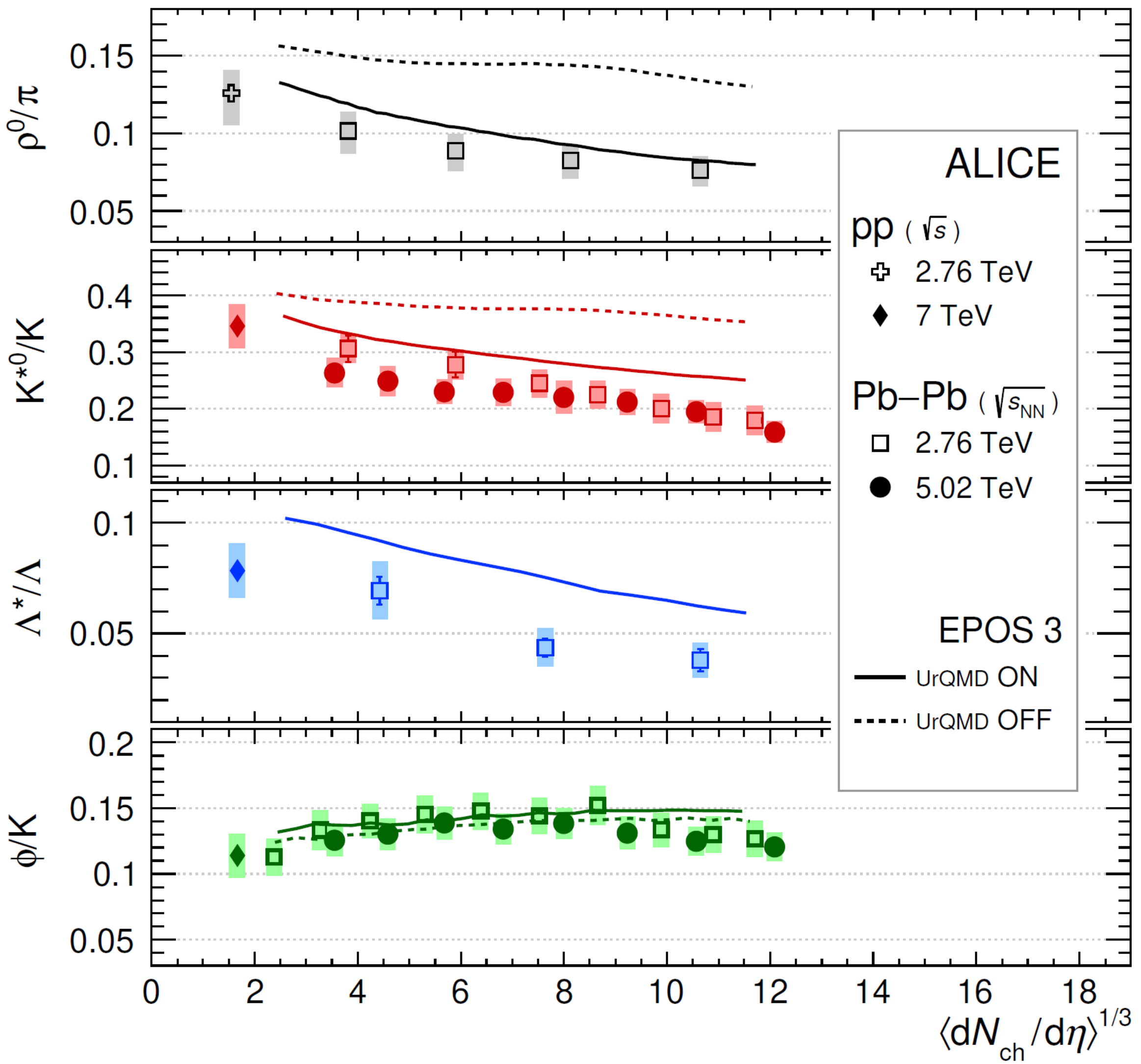


[ALICE, PLB 822 (2021) 136579](https://doi.org/10.1016/j.physletb.2021.136579)

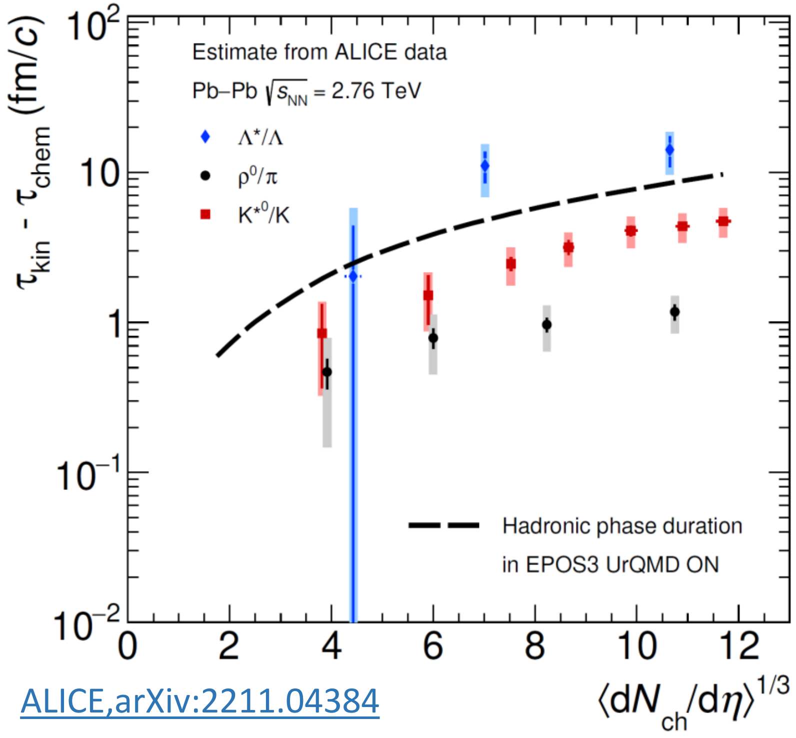


- Different states have different binding energies. Loosely bound states melt first!
- Sequential suppression of individual states provides a "thermometer" of the QGP
- Charmonium: sequential suppression + regeneration effects
- Bottomonium: sequential suppression

Probing hadronic phase with resonances



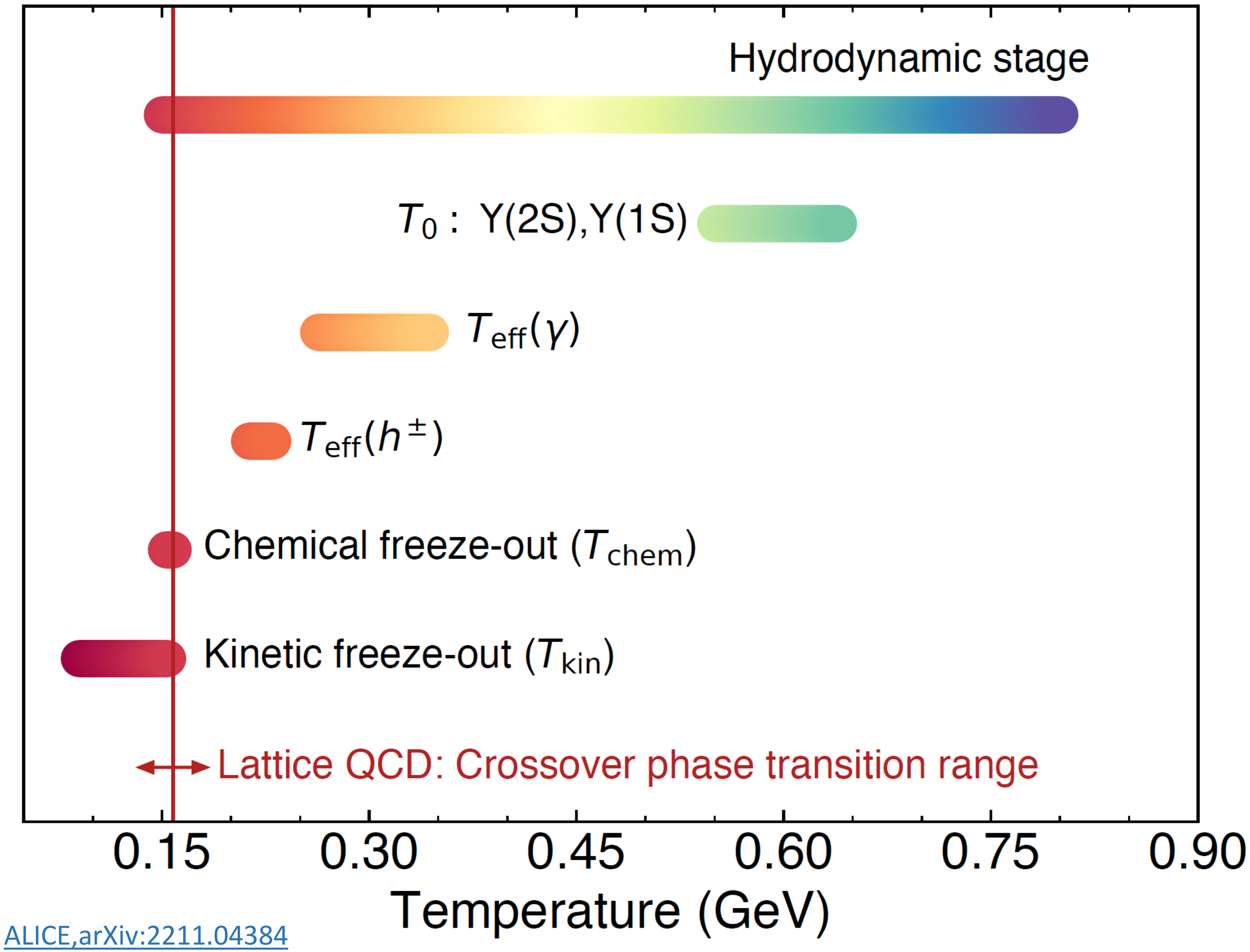
ALICE,arXiv:2211.04384



ALICE,arXiv:2211.04384

- Suppression of short-lived resonances increasing from peripheral to central collisions
- Possible interpretation: rescattering of resonance decay products in the hadronic phase
  - Hadronic phase duration 1 – 10 fm/*c*
  - Times estimated from different resonances differ by order of magnitude. Different freeze-out times for different species?

Temperature scales

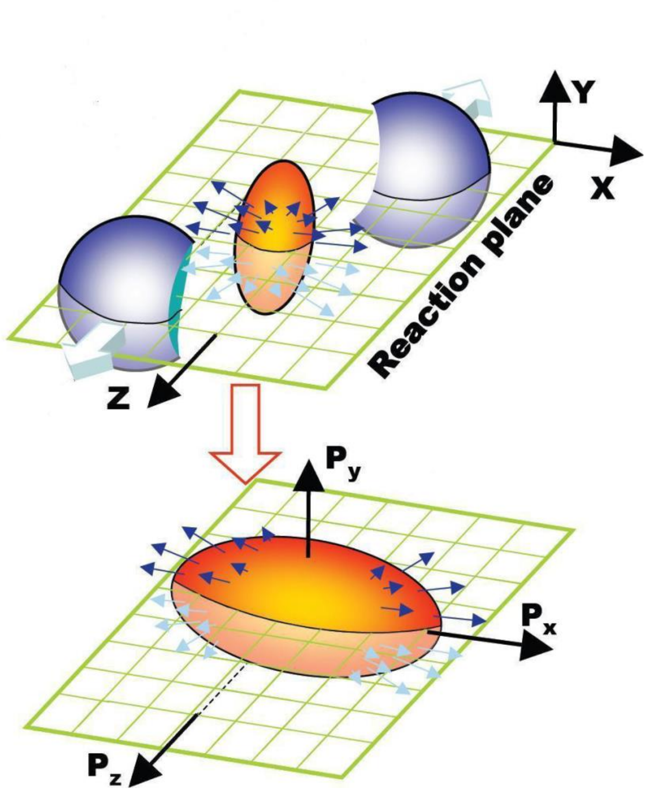


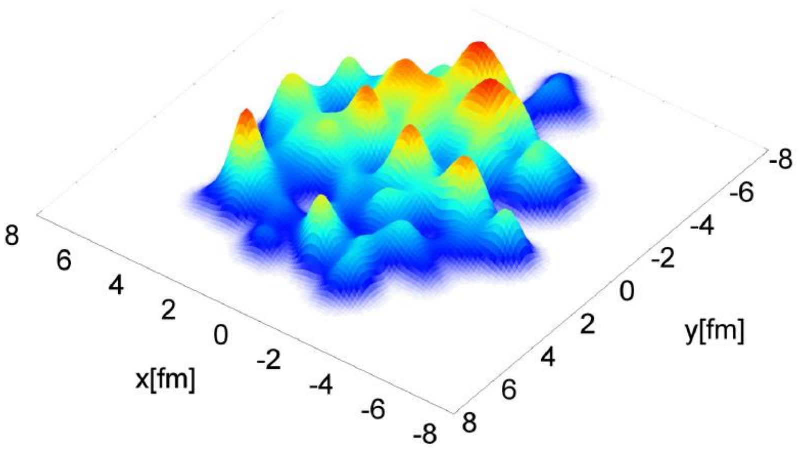
ALICE,arXiv:2211.04384

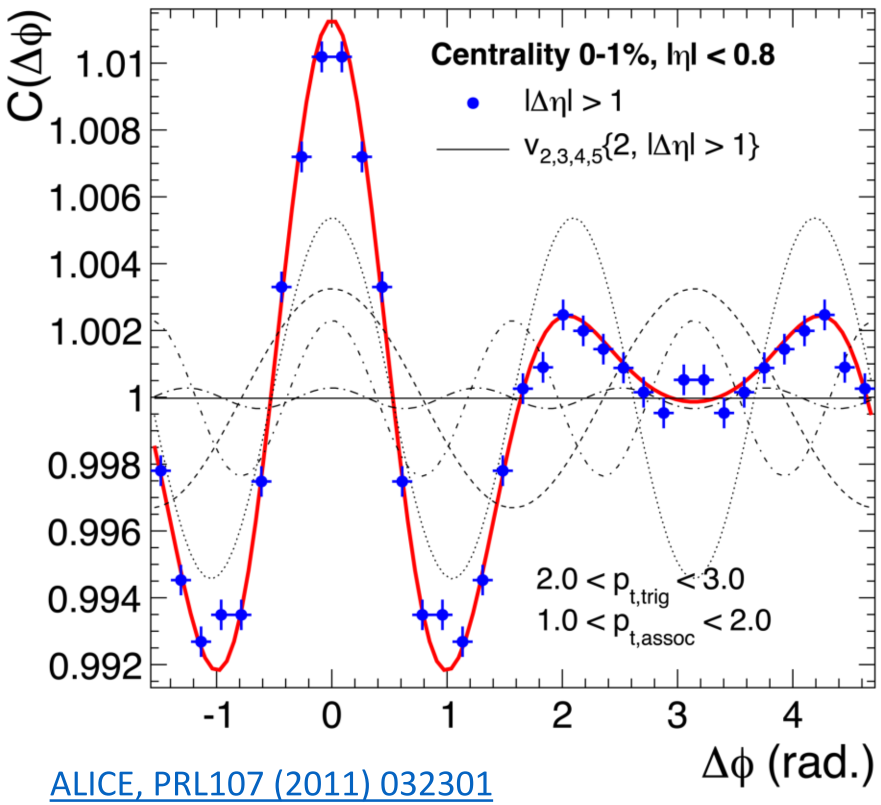
Many observables imply temperatures far greater than T_c

- Sequential melting of quarkonium states
- Effective thermal photon $T \sim 2T_c$
- Chemical freeze-out ~ T_c

Anisotropic flow





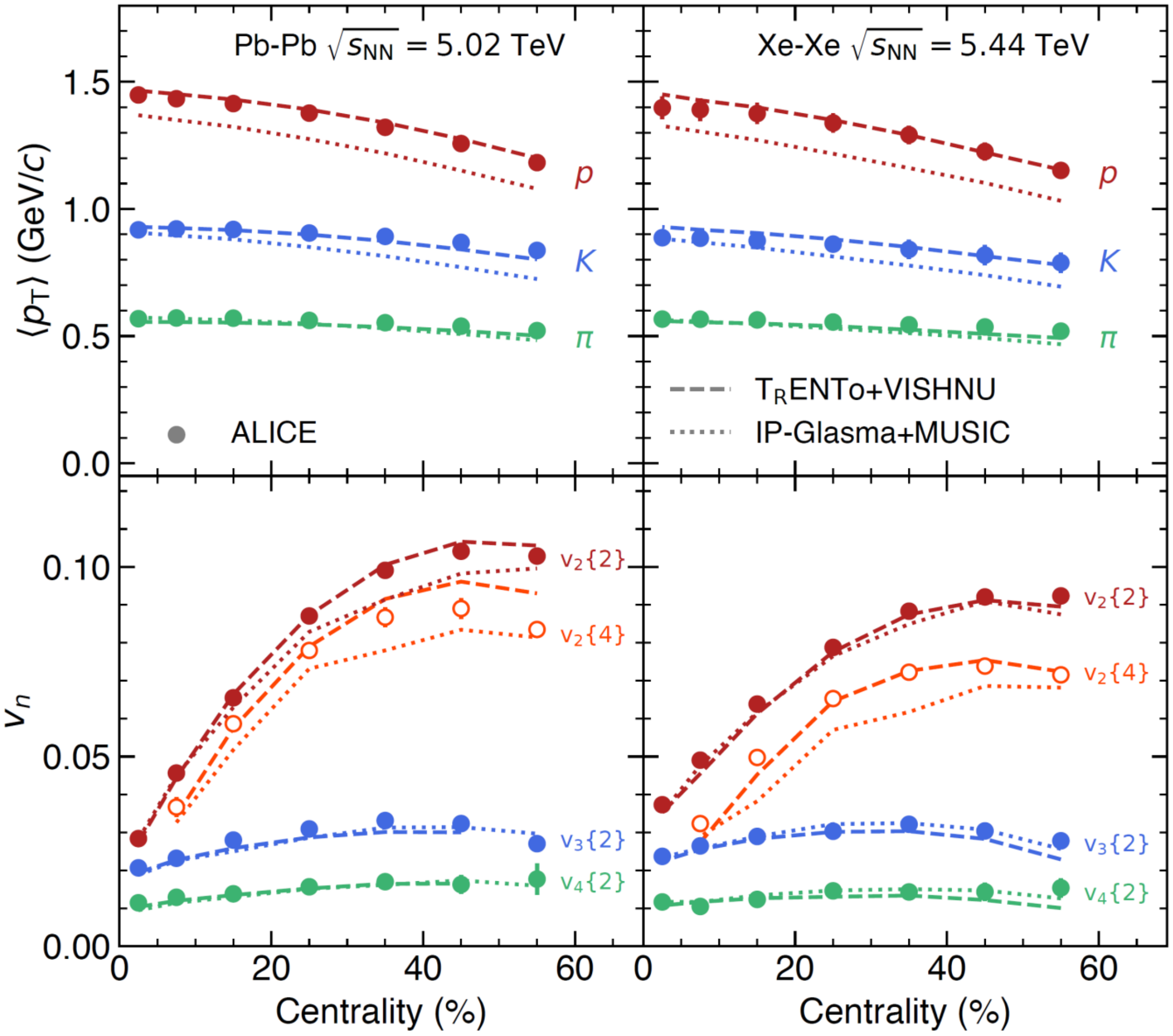


ALICE, PRL107 (2011) 032301

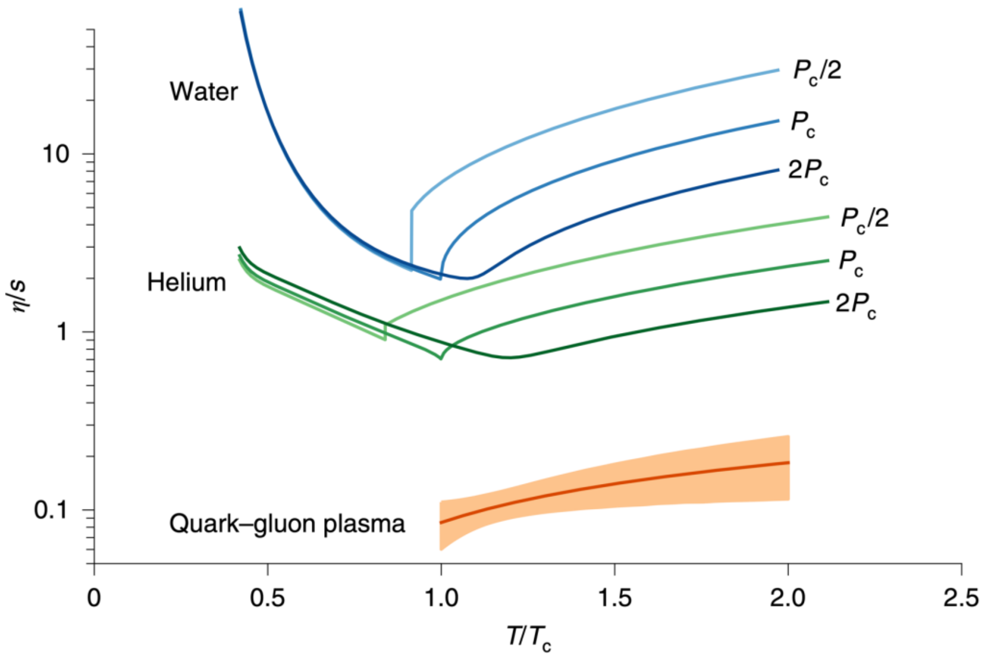
$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2v_n(p_T)\cos\left(n(\phi - \Psi_n)\right)$$

- Spatial anisotropy and density fluctuations of the initial state induce momentum anisotropy via QGP response
- Characterised by anisotropic flow coefficients v_n

QGP properties from anisotropic flow



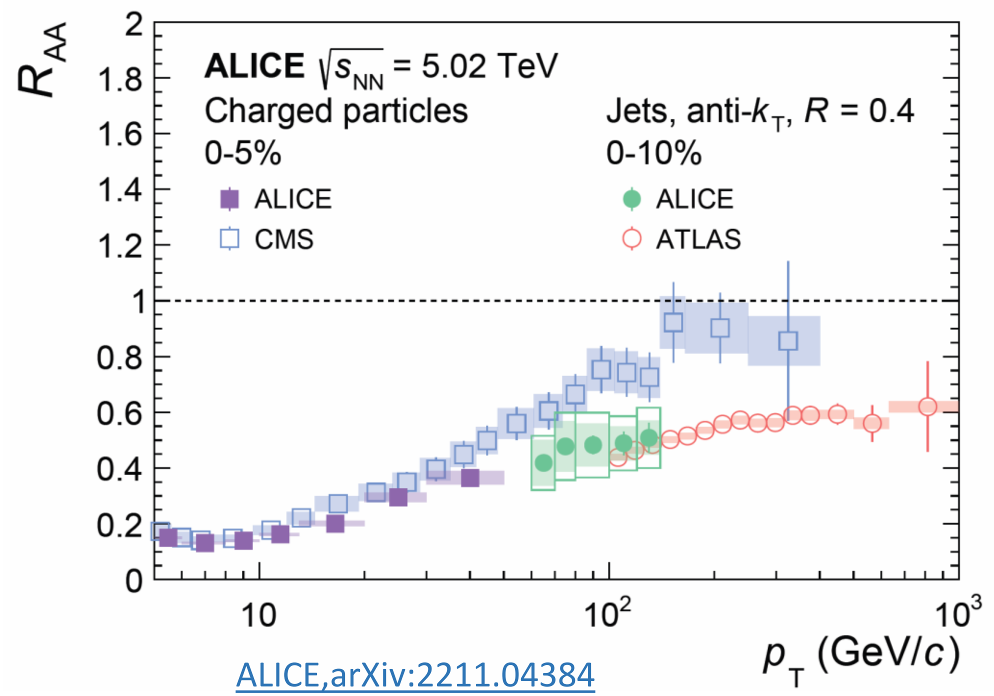
ALICE,arXiv:2211.04384



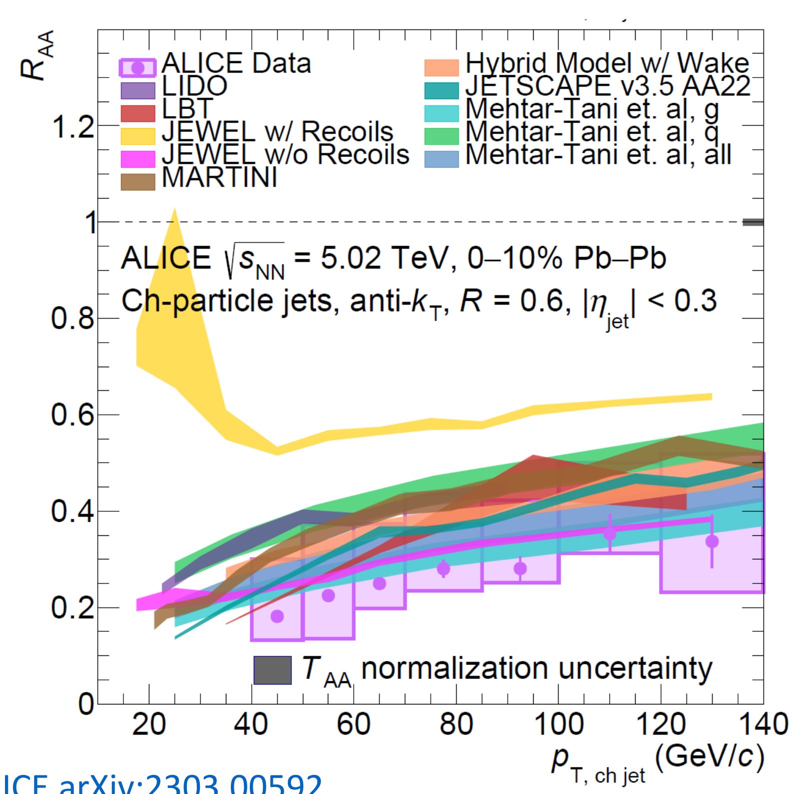
ALICE,arXiv:2211.04384

- Global radial and anisotropic expansion of QGP described by hydrodynamical equation of state with small viscosity close to Ads/CFT limit
- QGP is strongly coupled at this temperature scale

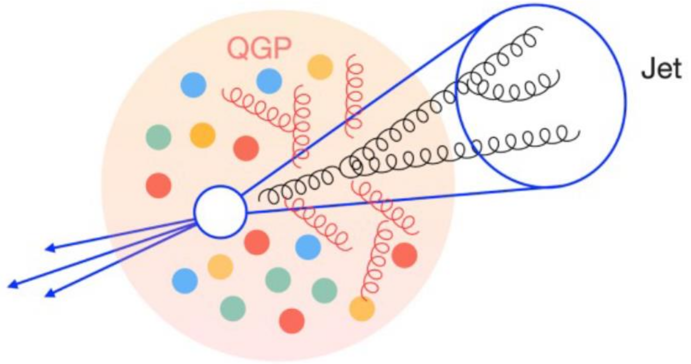
Hard probes



ALICE,arXiv:2211.04384



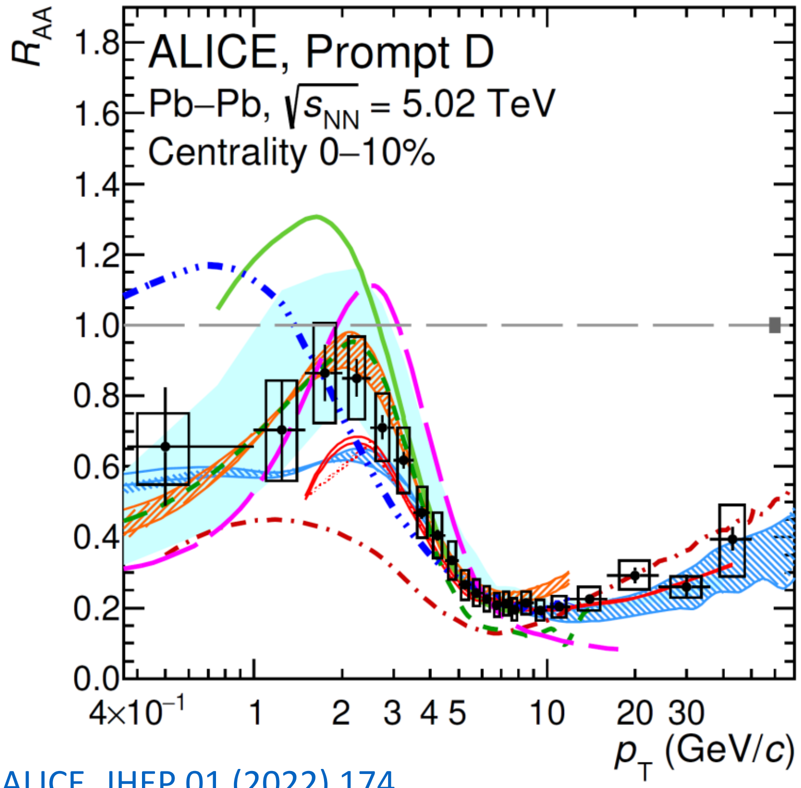
ALICE,arXiv:2303.00592



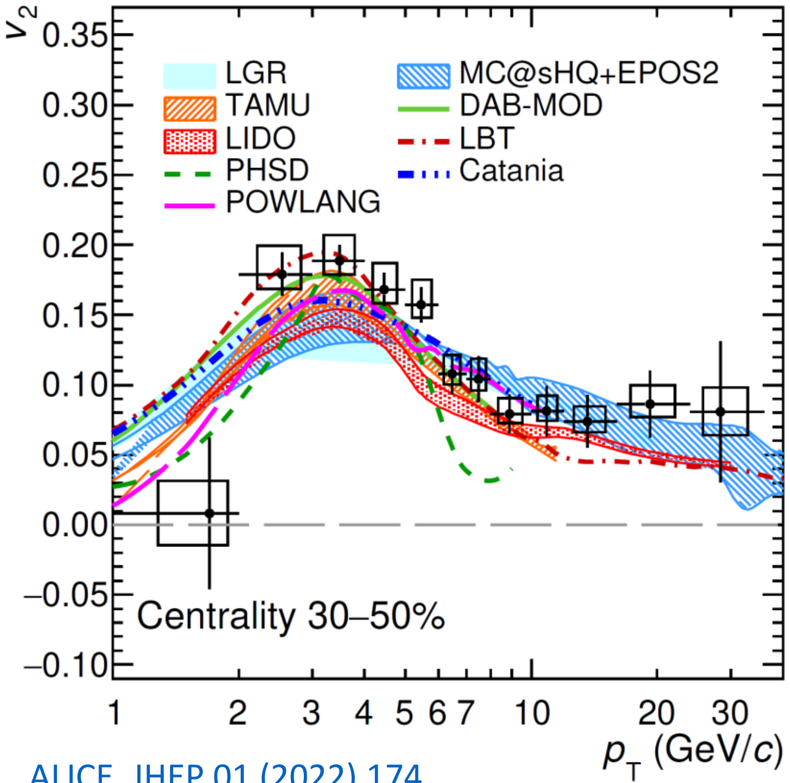
https://www.int.washington.edu/node/776

- Jet and high p_T hadron suppression observed over extensive range
- Explained by energy loss of hard partons interacting with QGP medium
  - Dominated by radiative emission. Extracted energy loss: 8 ± 2 GeV
- New ML-based techniques allow for the extension to lower p_T and larger R = 0.6

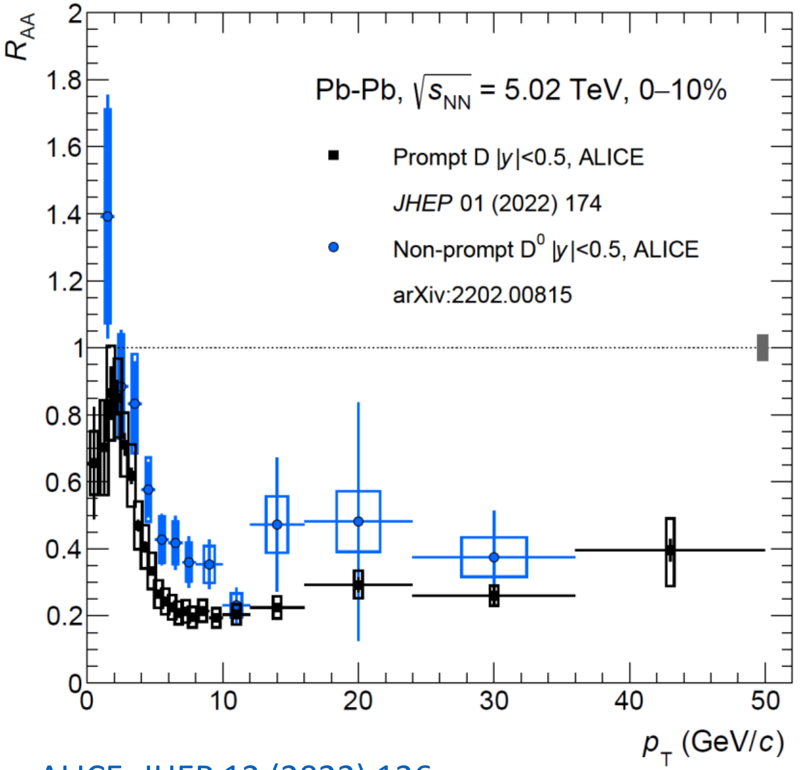
Heavy flavours



ALICE, JHEP 01 (2022) 174



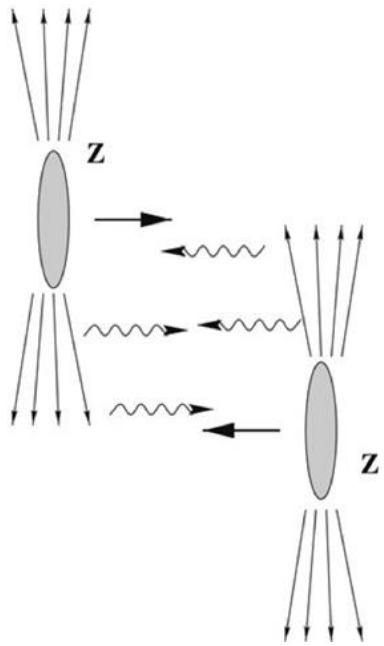
ALICE, JHEP 01 (2022) 174

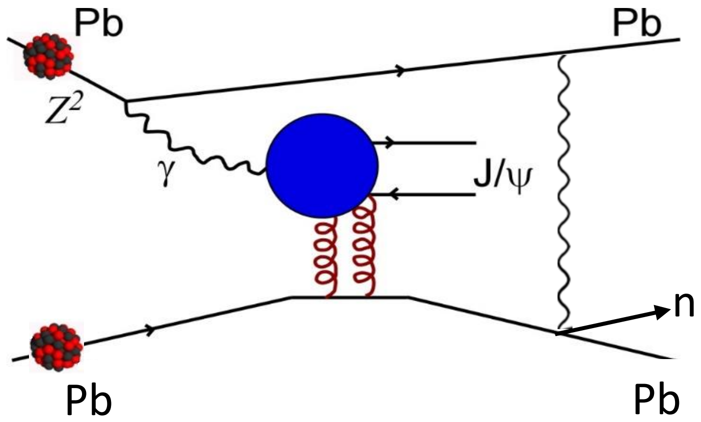


ALICE, JHEP 12 (2022) 126

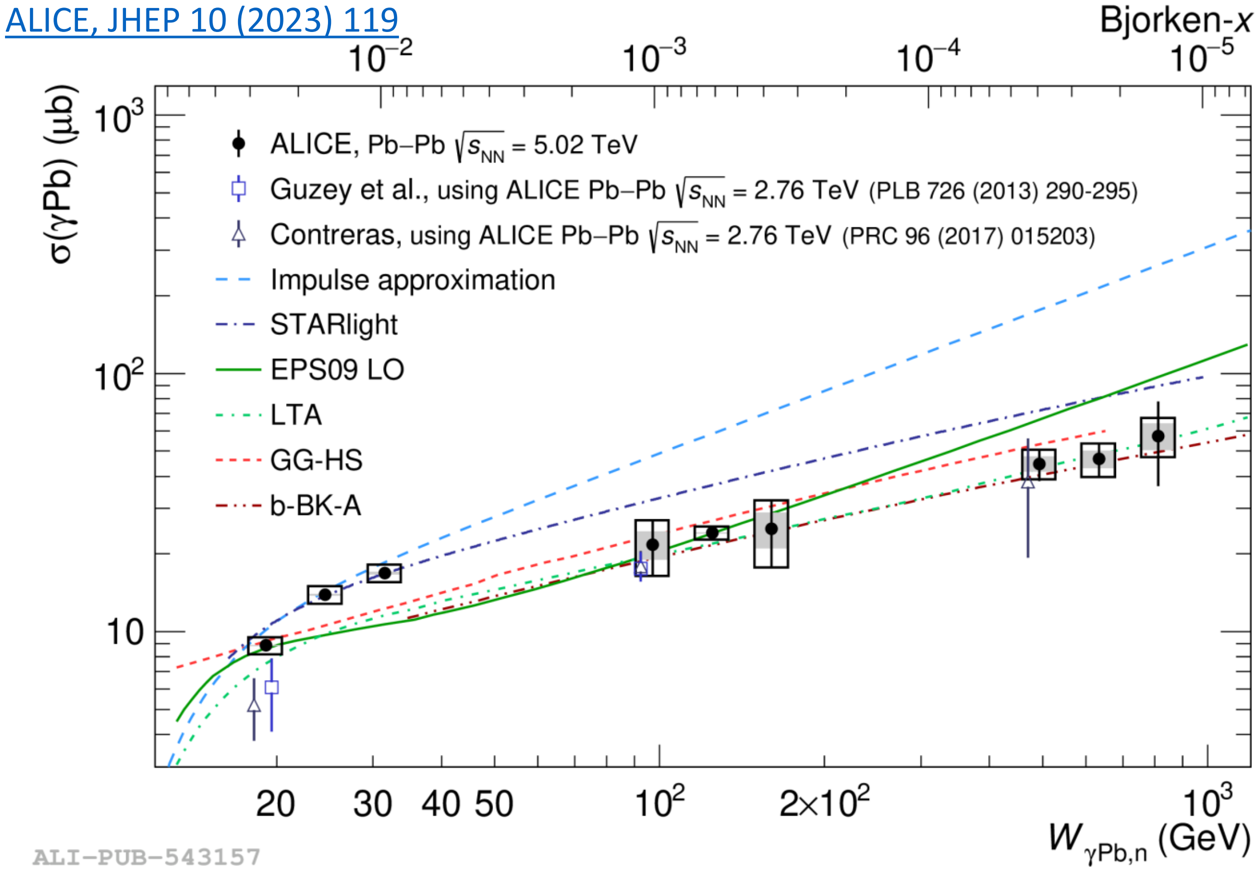
- D-meson spectra measured down to 0 p_T
- Challenge for charm-quark transport models to describe both the R_{AA} and anisotropic flow (v_2):
  - providing constraints on heavy-quark spatial diffusion coefficient: $1.5 < 2\pi D_s T_c < 4.5$
- D mesons from bottom decays are less suppressed than those formed from charm
  - Indication of mass dependent radiative losses in agreement with expectations from QCD

Initial state with ultra-peripheral collisions



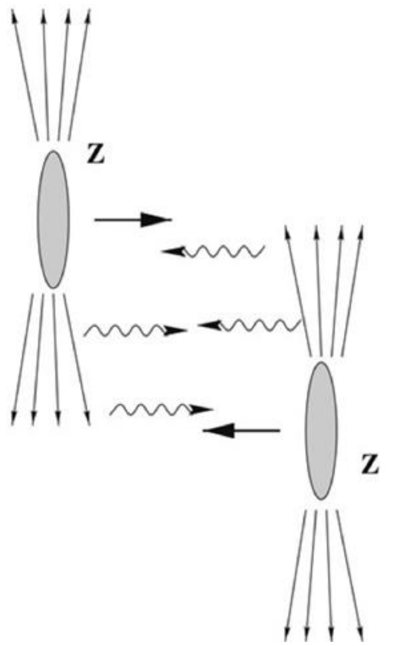


ALICE, JHEP 10 (2023) 119

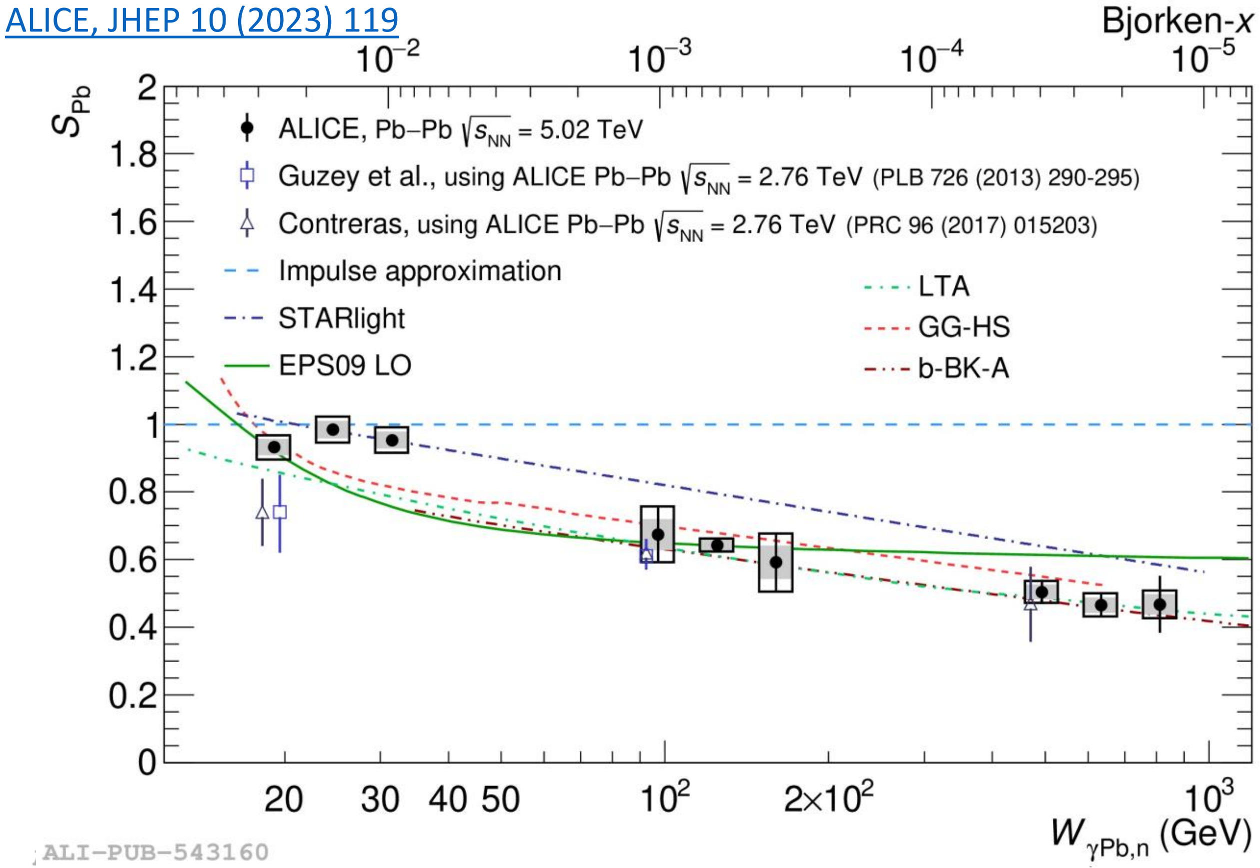


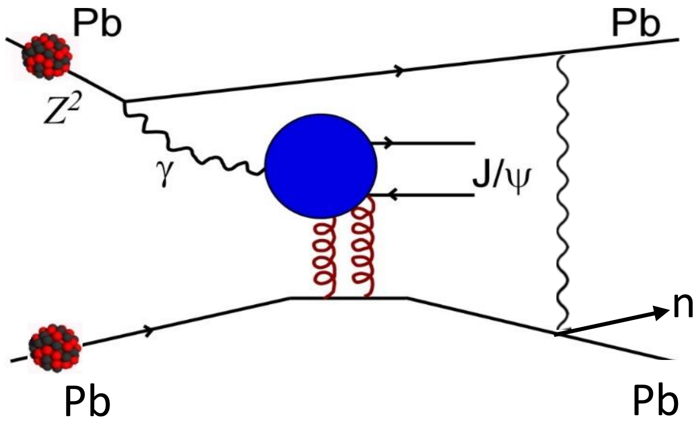
- Coherent J/ψ photoproduction: probing low-x gluon PDFs in the nucleus
- Neutron emission due to EMD helps to decouple low-*x* and high-*x* contributions

Initial state with ultra-peripheral collisions



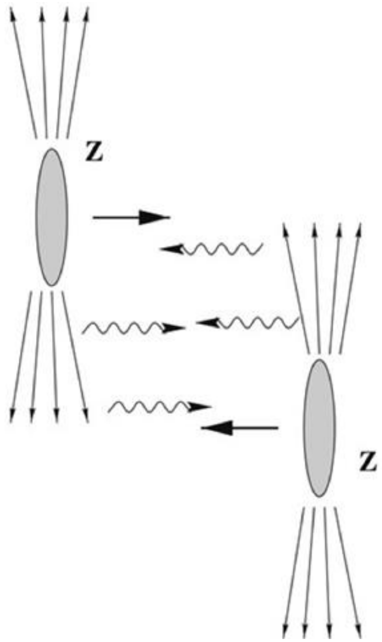
ALICE, JHEP 10 (2023) 119



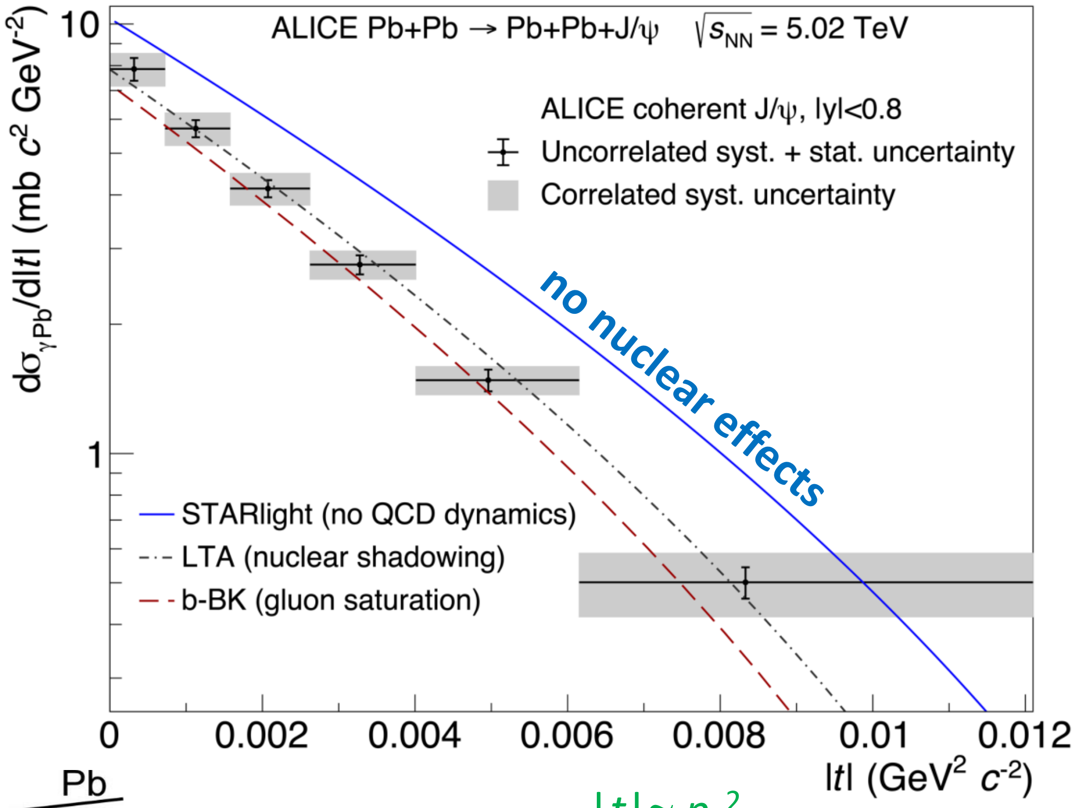


- Coherent J/ψ photoproduction: probing low-x gluon PDFs in the nucleus
- Neutron emission due to EMD helps to decouple low-*x* and high-*x* contributions
- Comparison with the impulse approximation (no nuclear effects) allows for extraction of the gluon shadowing factor: $R_g \sim 0.5$ at $x \sim 10^{-5}$

Probing transverse profile of Pb nuclei

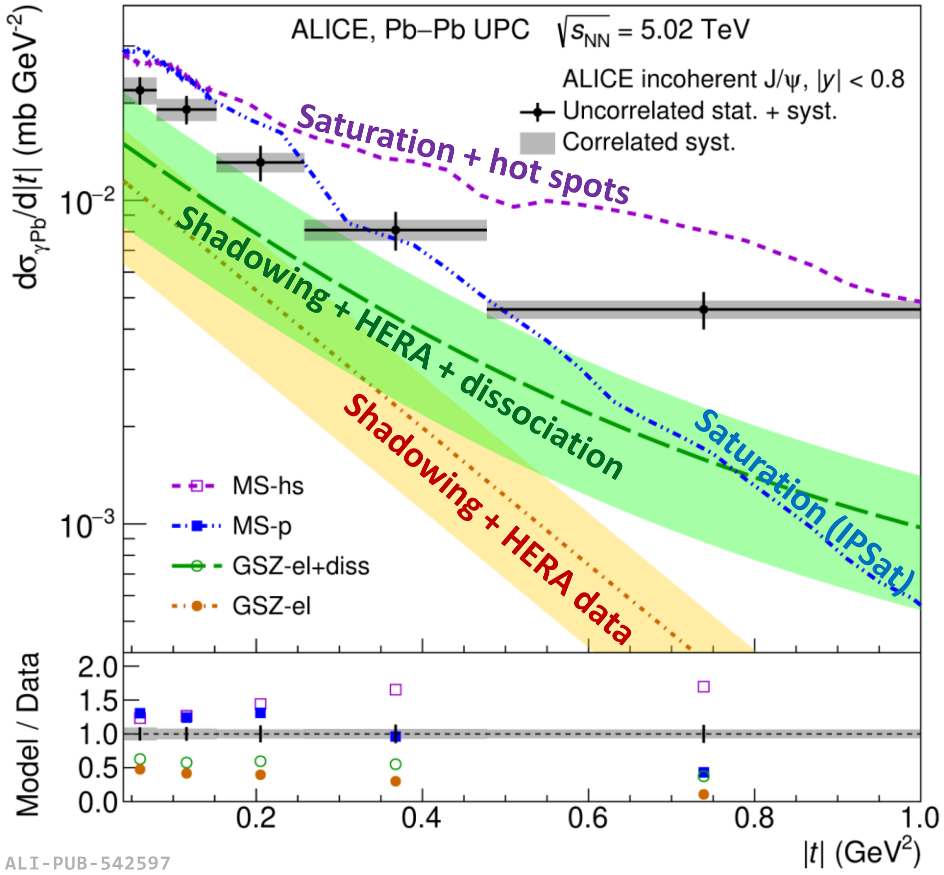


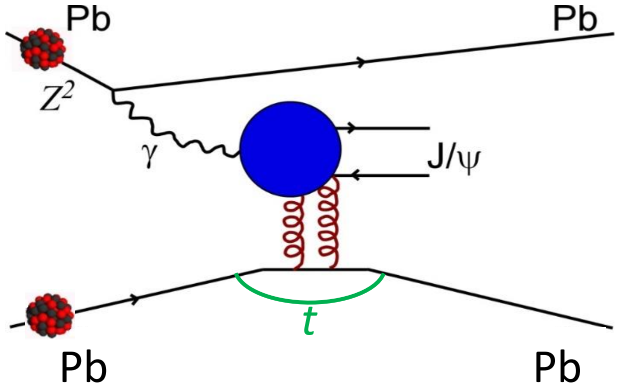
ALICE, PLB 817 (2021) 136280



$|t| \approx p_T^2$

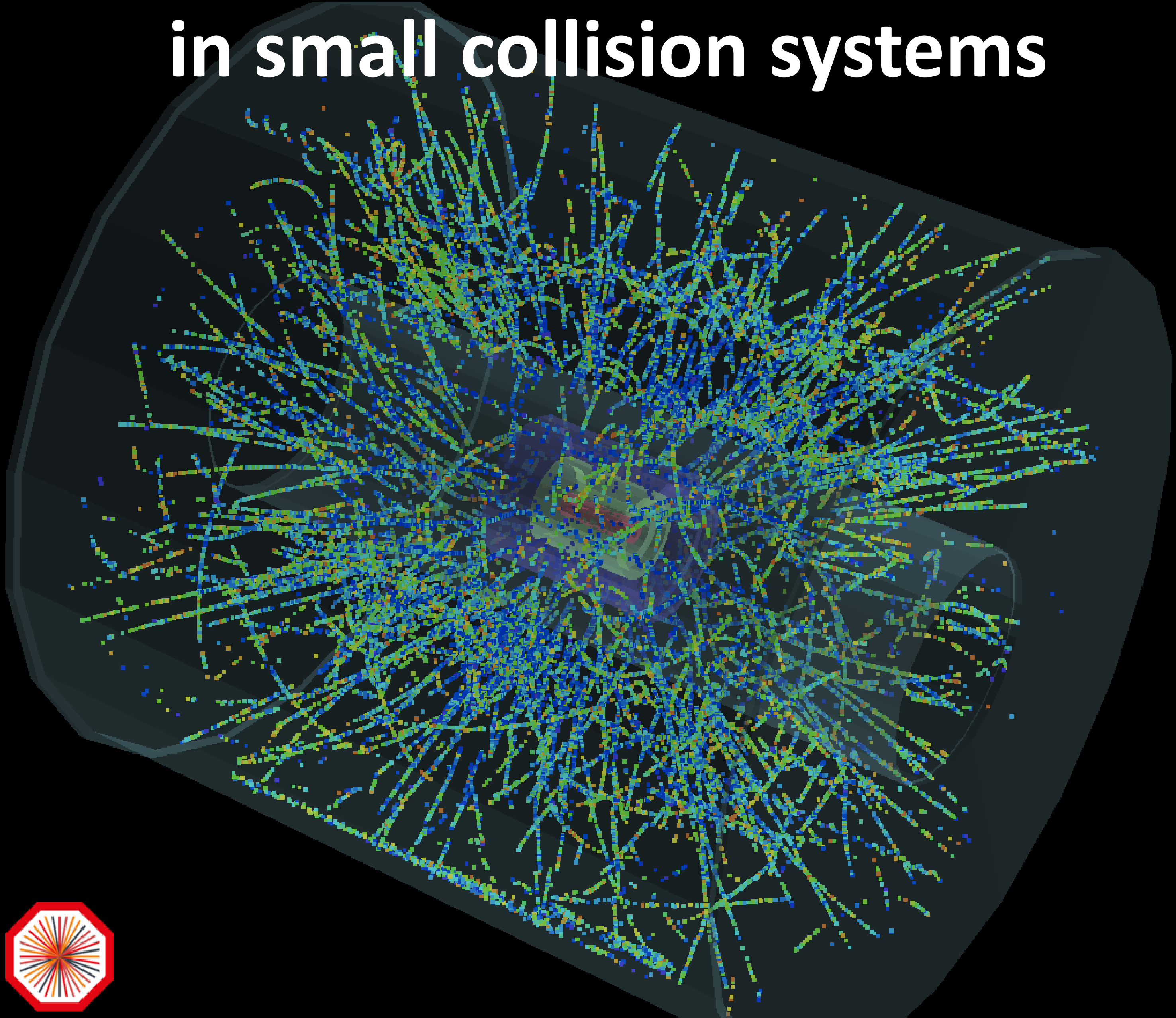
ALICE, arXiv:2305.06169





- Coherent J/ψ: *t*-dependence sensitive to transverse gluon distribution
  - need shadowing/saturation effects to describe the data
- Incoherent J/ψ: *t*-dependence sensitive to the variance of the gluon field
  - data better described by models with sub-nucleon degrees of freedom

QGP-like effects in small collision systems



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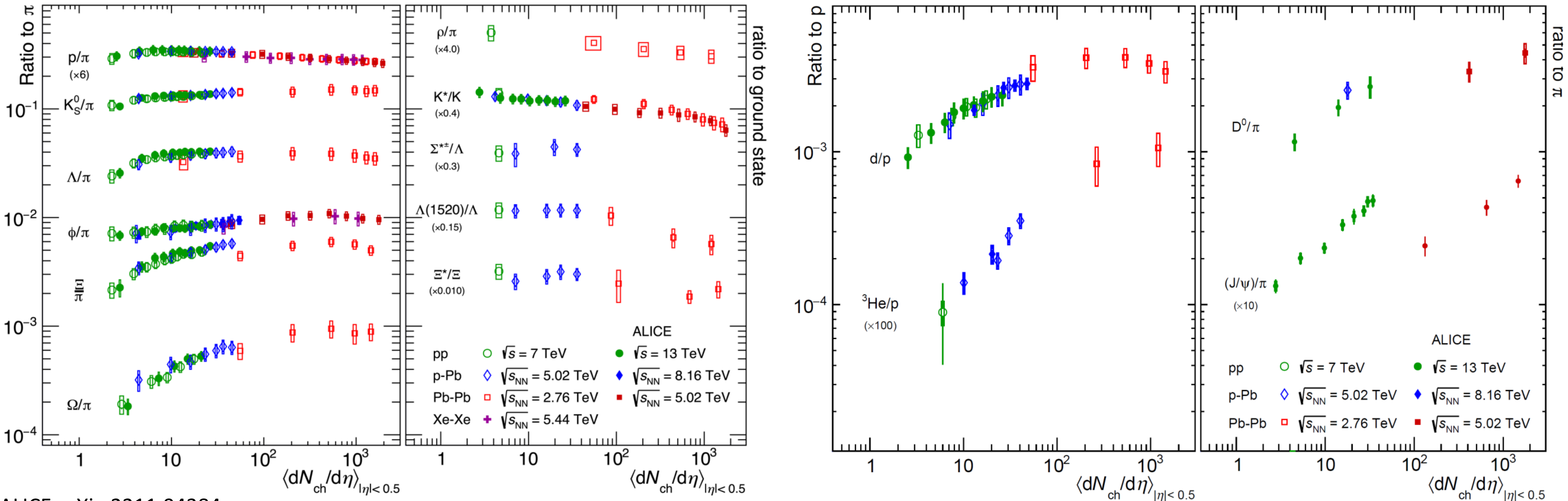
pp 7 TeV (June 2010)

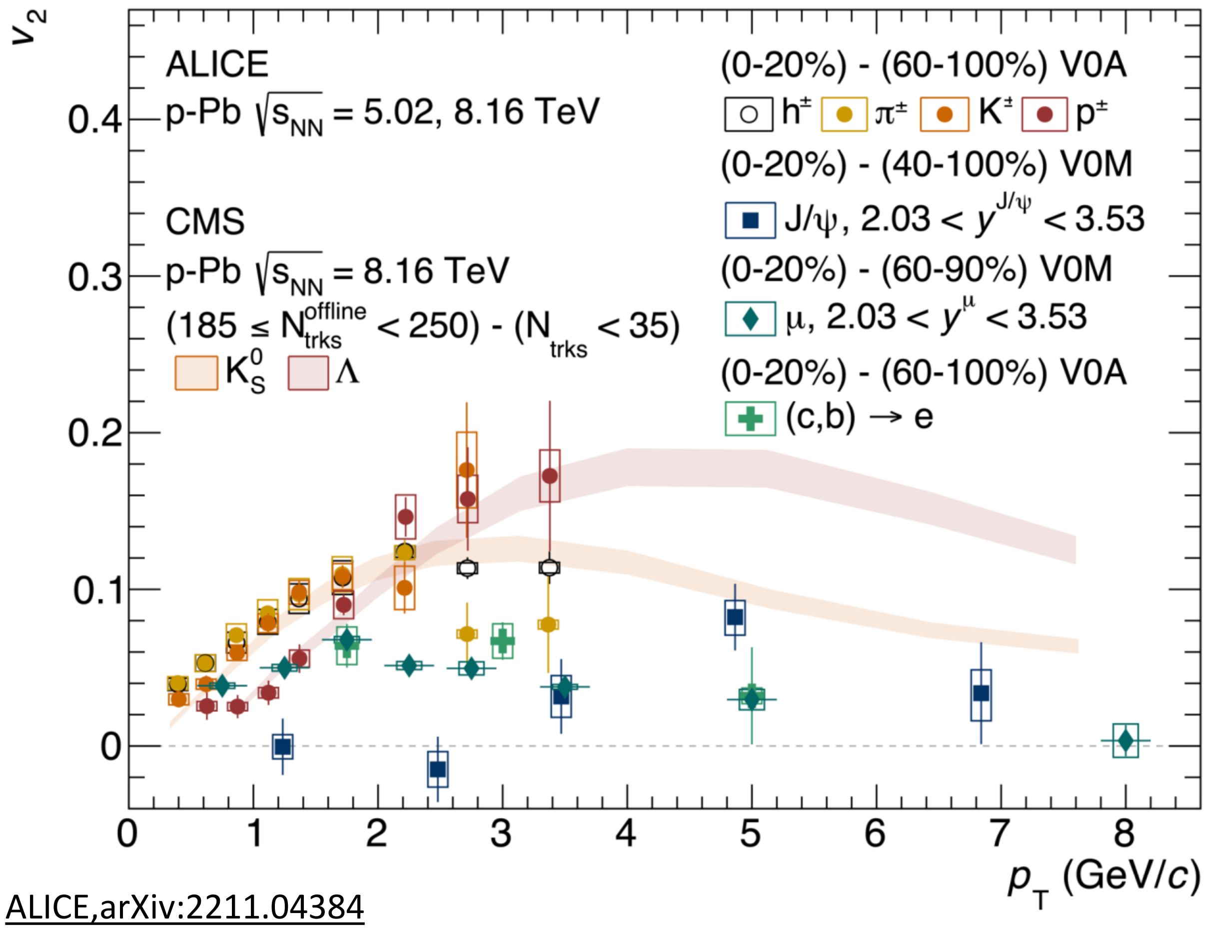
Enhancement of particle yields

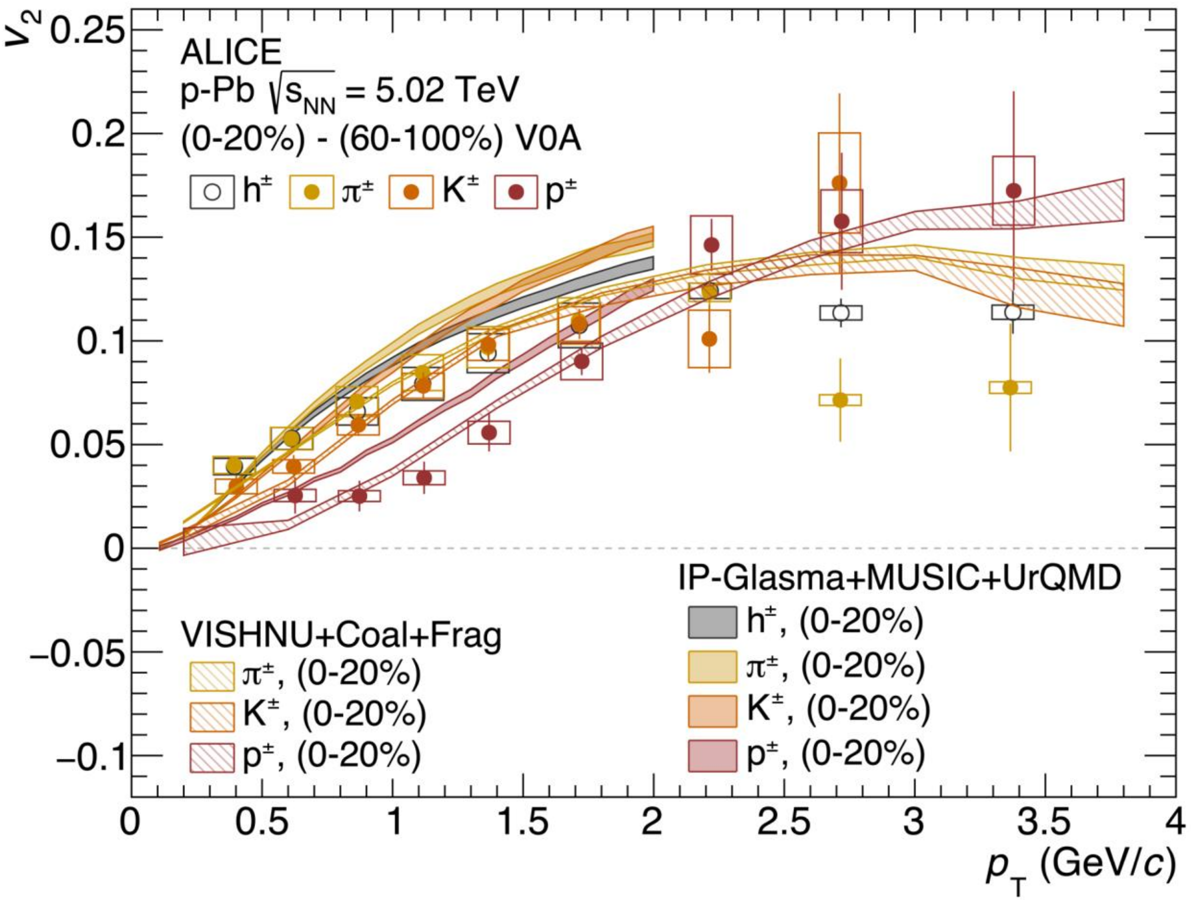


ALICE,arXiv:2211.04384

- Yields of strange and charm particles relative to pions increase with multiplicity
- Same trend for light nuclei relative to protons
- Reaching highest multiplicity ratios comparable with Pb-Pb
- Non-QGP effects playing a role?

Flow in small systems



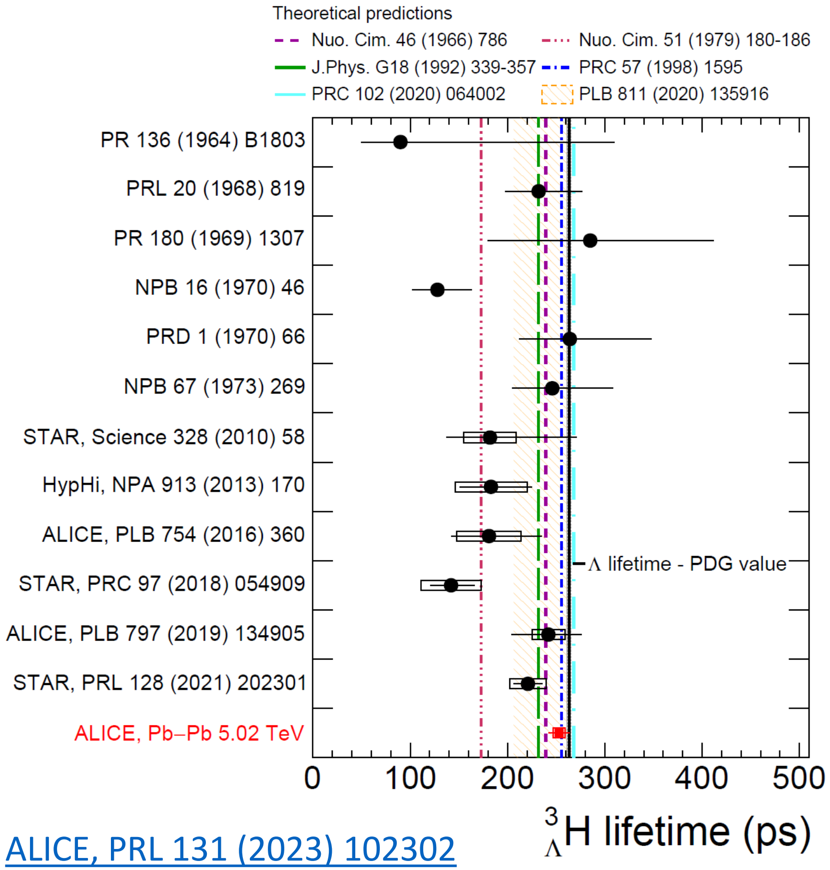


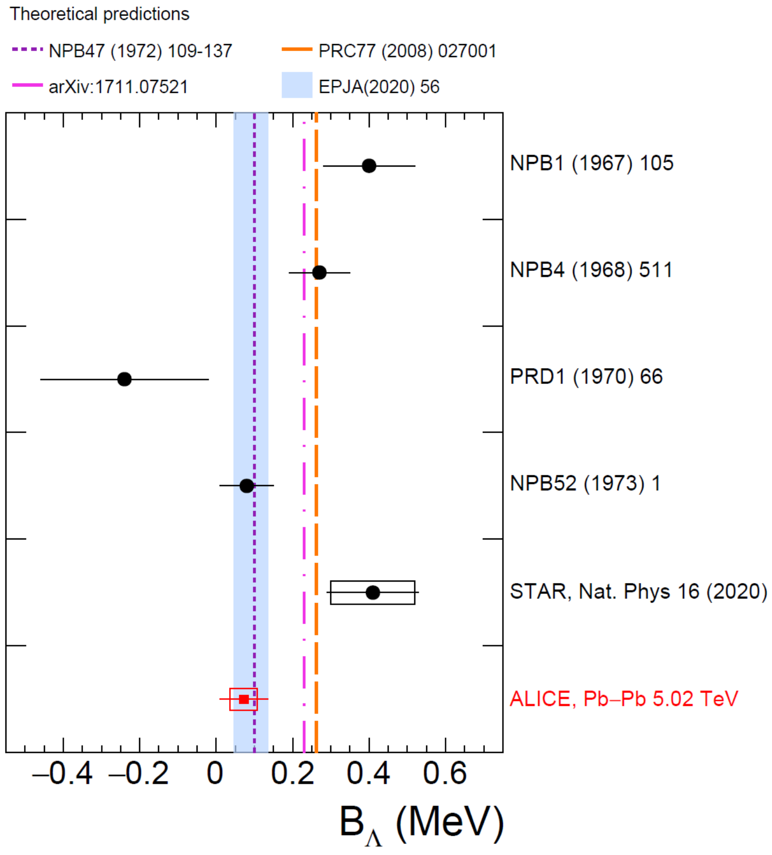
ALICE,arXiv:2211.04384

- Light and charmed hadrons exhibit anisotropic flow in small systems
- Light sector described by hydrodynamics with QGP equation of state

QCD aspects beyond QGP

Hypertriton lifetime



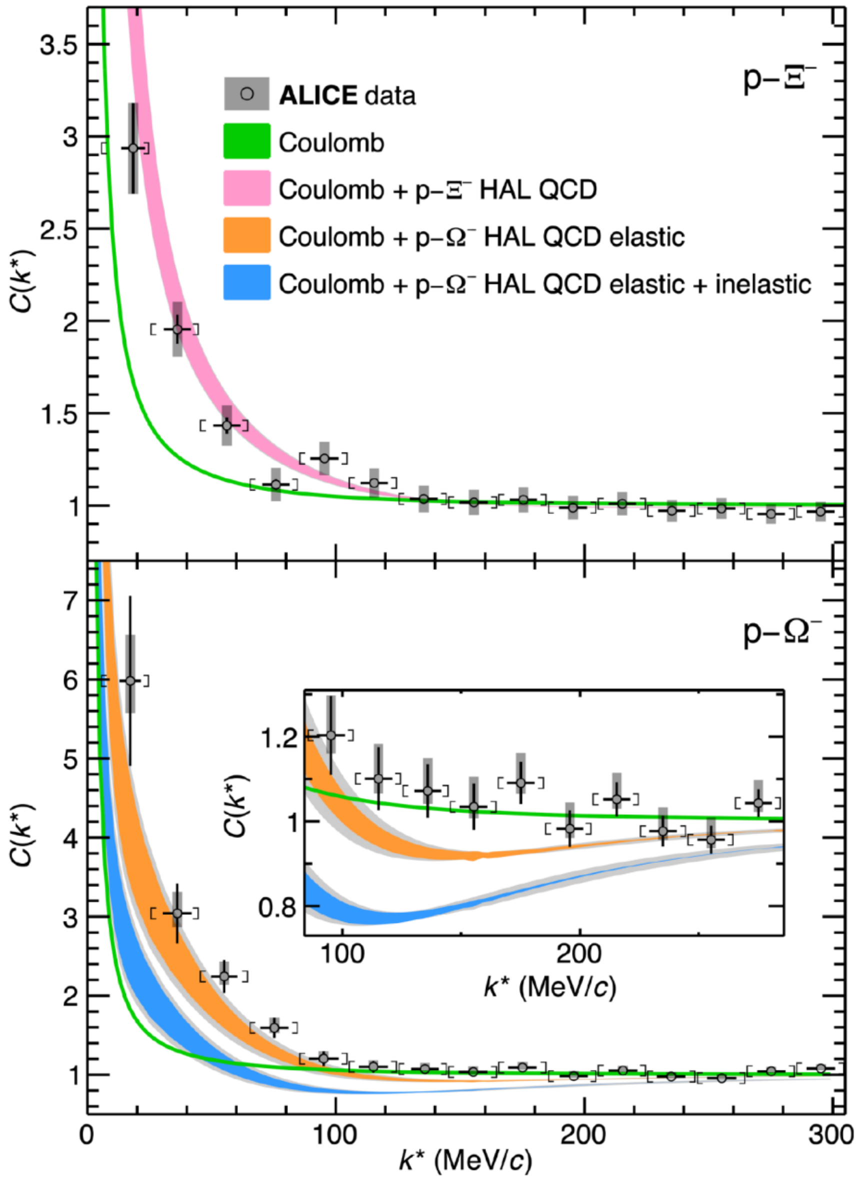


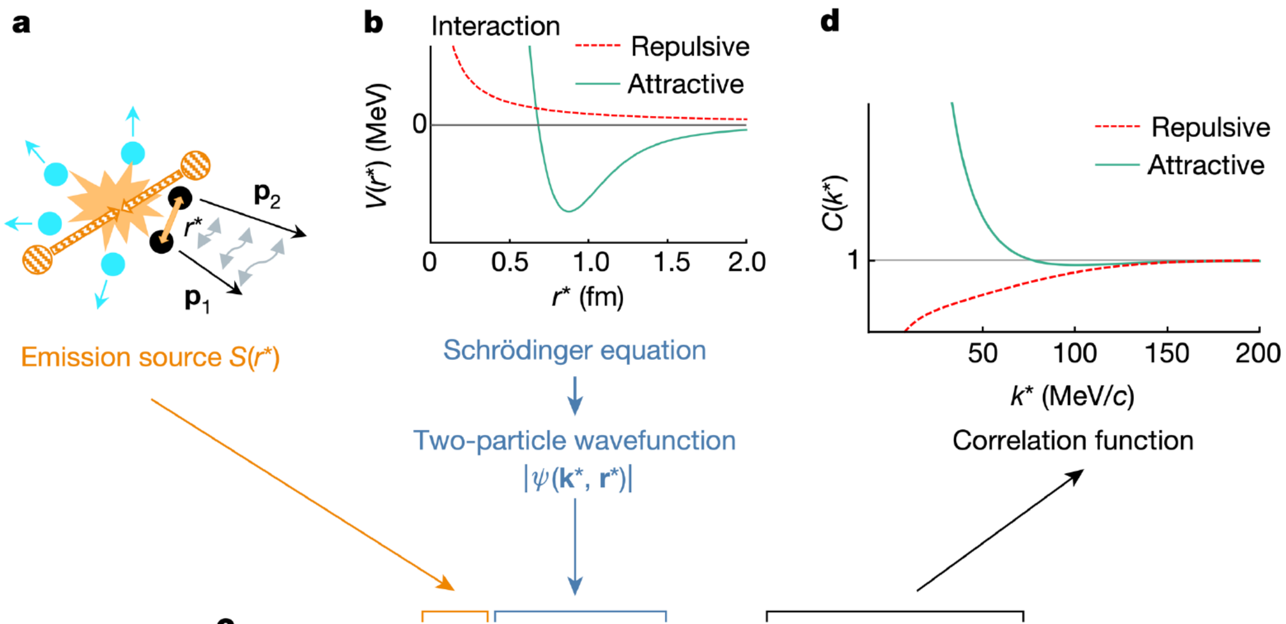
[ALICE, PRL 131 (2023) 102302]

- Unprecedented precision with Pb-Pb Run 2 data
- No deviation from the free Λ lifetime
- Binding energy = 130 ± 30 keV, one of the smallest binding energies observed

  → loosely bound d-Λ molecule
- Produced in Pb-Pb collisions, despite having size comparable to medium (~10 fm)

Probing proton-hyperon interactions





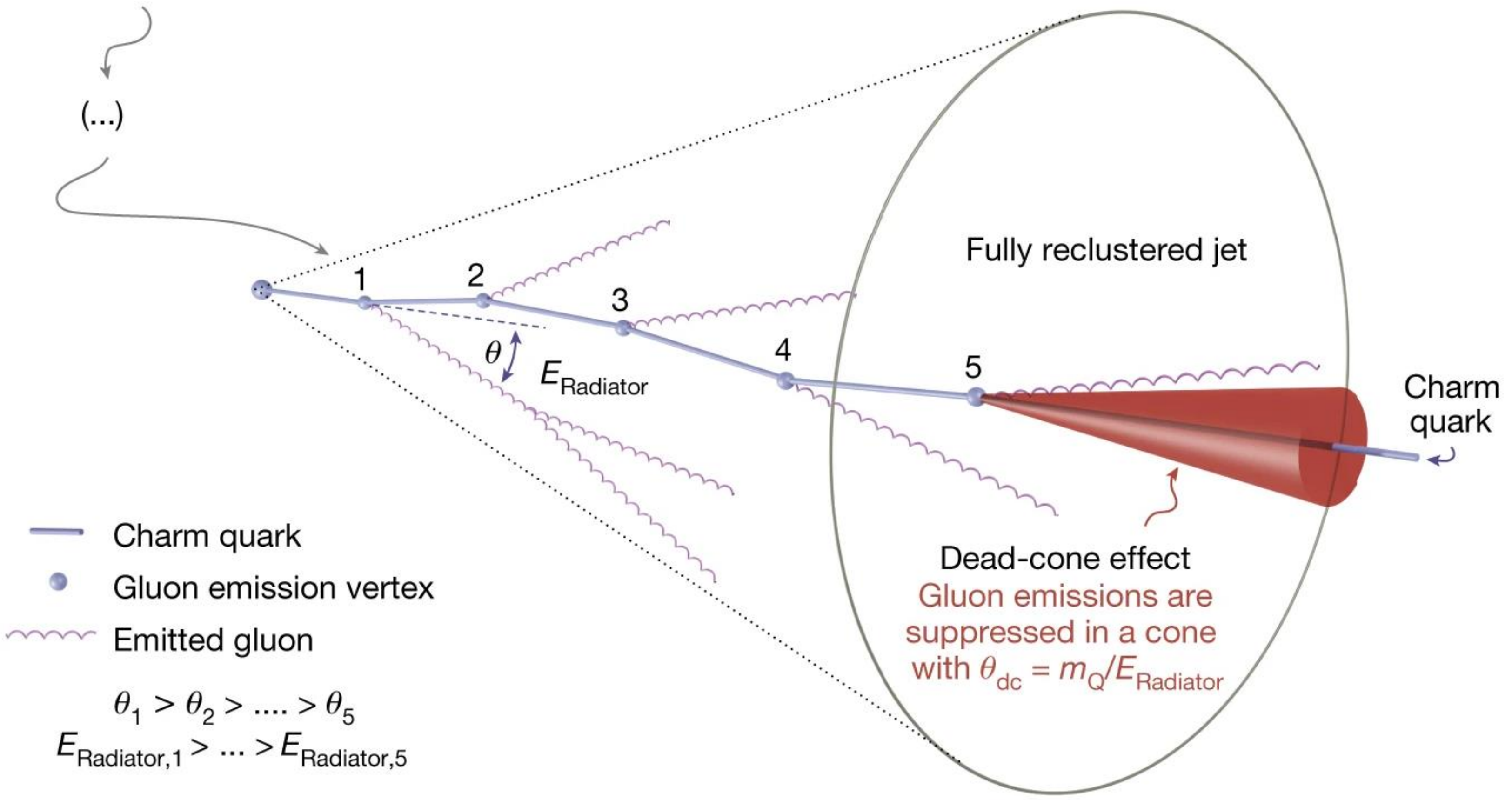
$$C(k^*) = \int S(r^*)\,|\psi(\mathbf{k}^*, \mathbf{r}^*)|^2\, d^3r^* = \xi(k^*)\,\frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

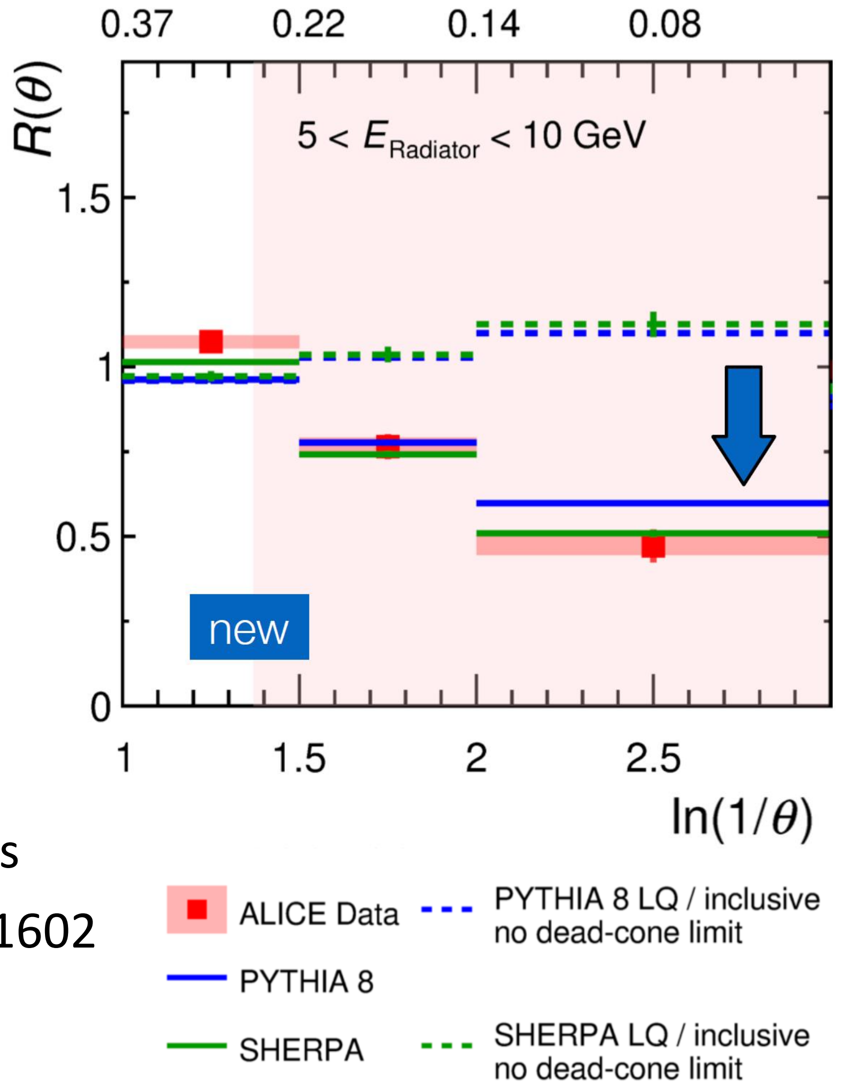
- Large production of hyperons provides unique opportunity to study rare hadronic interactions via femtoscopy measurements
- Strength of proton-hyperon interaction important for equation of state at high density → neutron stars

ALICE, Nature 588 (2020) 232

Dead cone effect

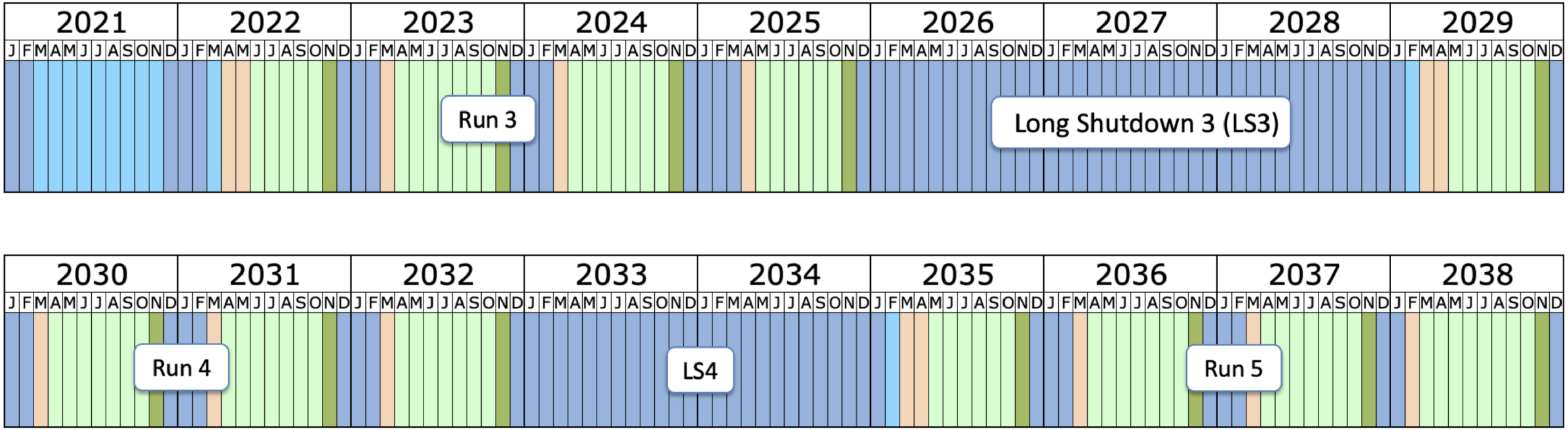
[ALICE, Nature 605 (2022) 440](#)





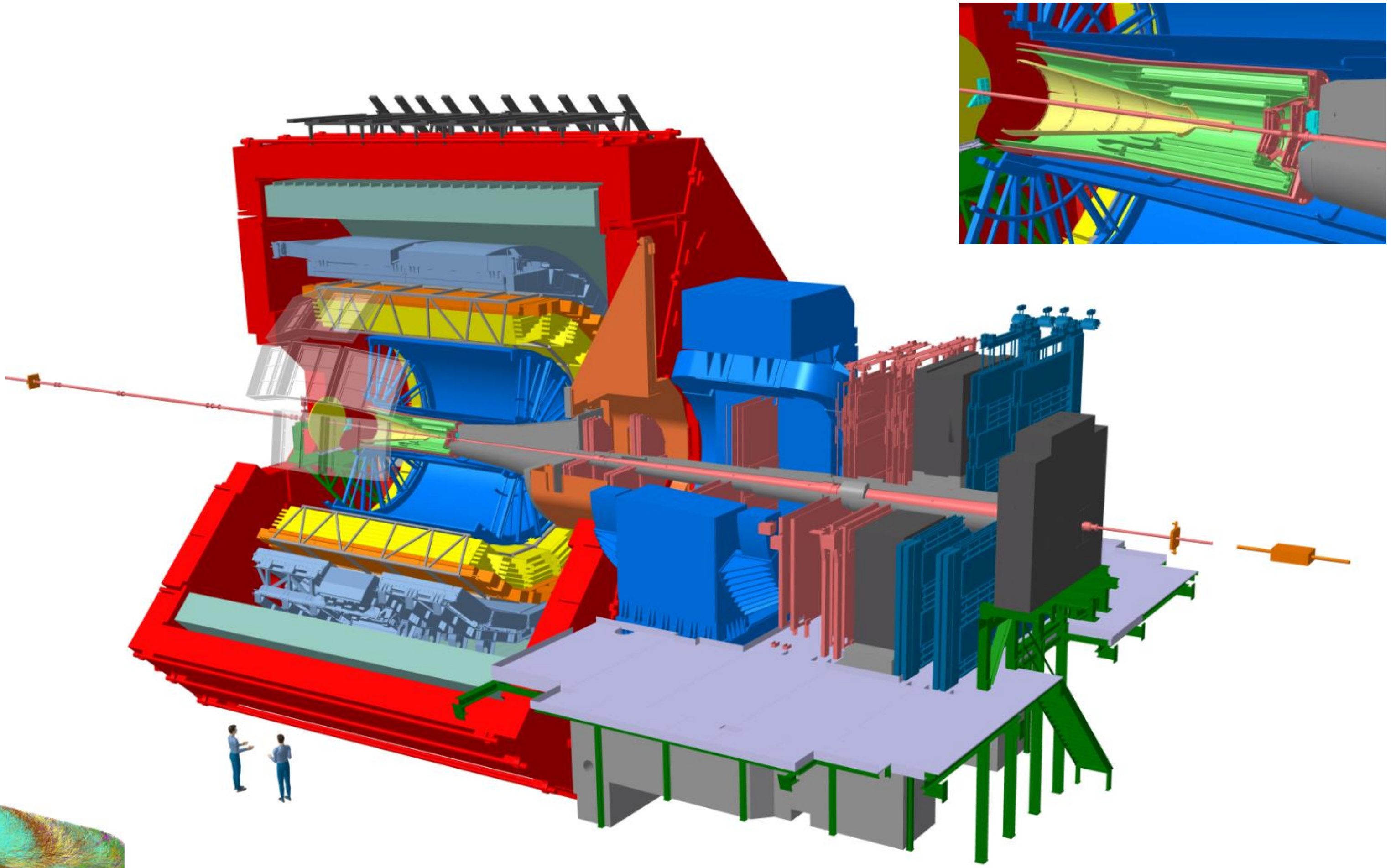
- Dead cone: suppression of gluon radiation from heavy quarks at small angles
- Predicted 30 years ago by Dokshitzer, Khoze and Troyan, J.Phys.G 17 (1991) 1602
- Part of modern parton shower models
- First direct observation with ALICE!

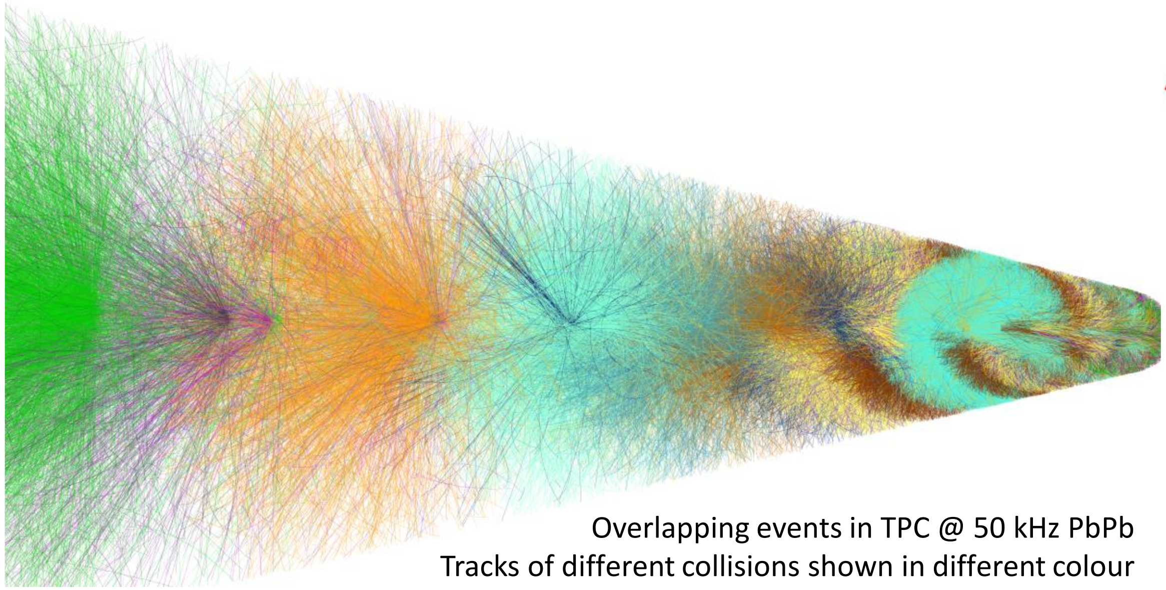
ALICE in Run 3 and beyond



ALICE in Run 3

- All-pixel Inner Tracking System
- GEM-based TPC readout
- Pixel Muon Forward Tracker
- Fast Interaction trigger
- New Online-Offline system
- Readout upgrade of all detectors



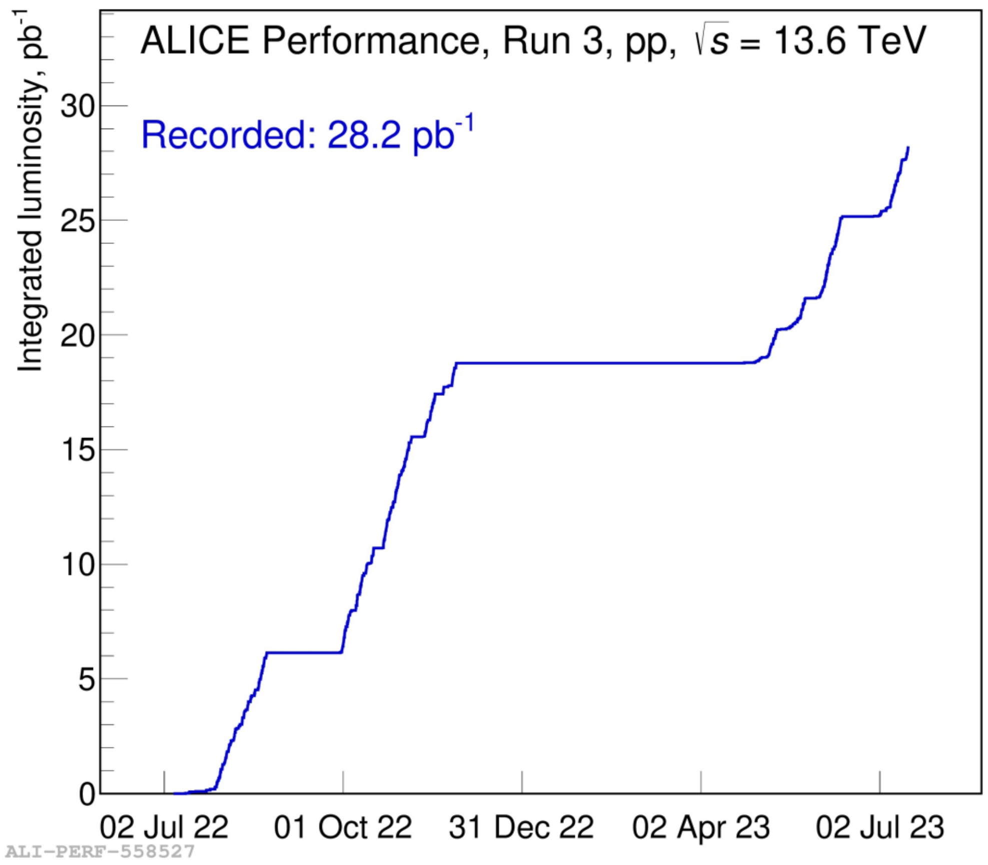


Overlapping events in TPC @ 50 kHz PbPb
Tracks of different collisions shown in different colour

Main goals:

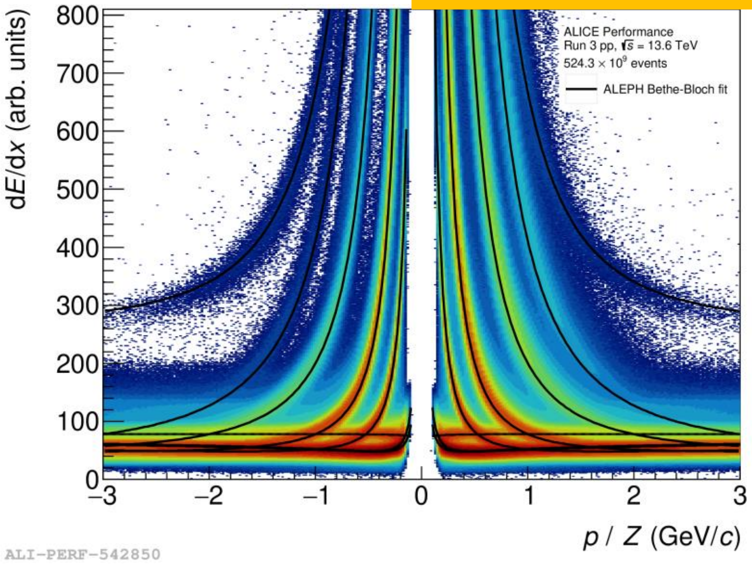
- Collect 13/nb in Run 3 and 4
  (x100 larger minimum bias statistics)
- Improve tracking precision by a factor 3-6

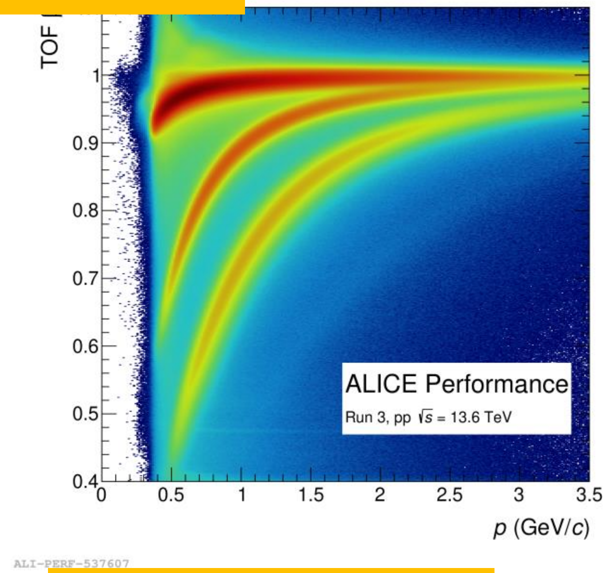
ALICE performance in Run 3: pp data taking



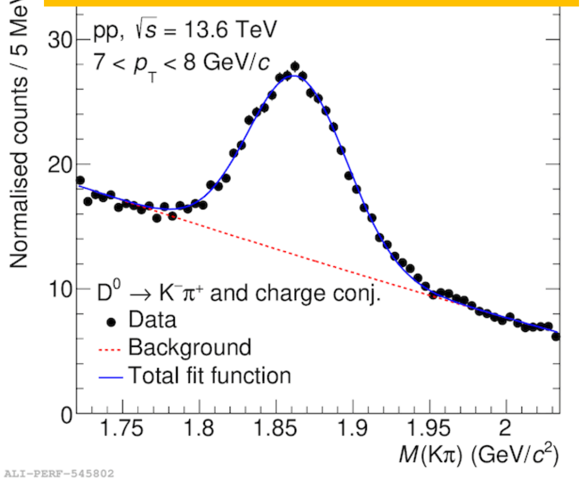
- **pp** data taking at **~500 kHz**
- Permanent storage of 10^{-4} selected time frames: using high-level software-based triggers

Excellent PID performance!

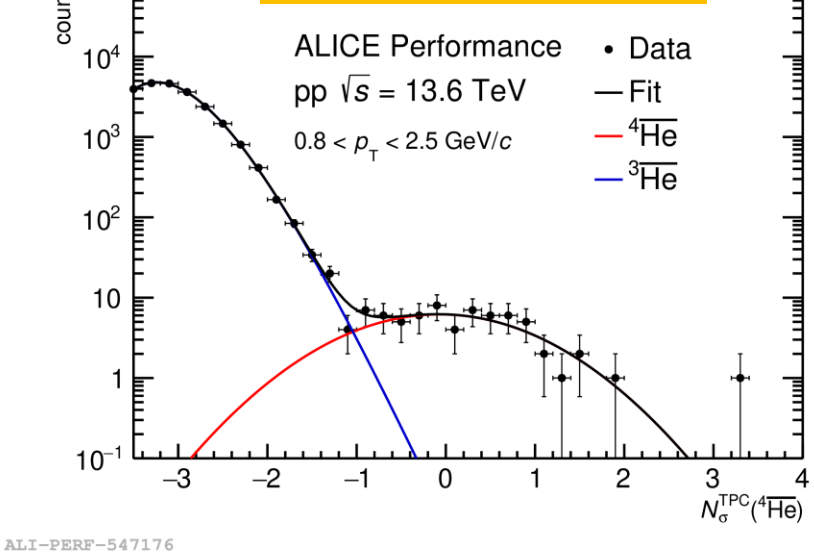


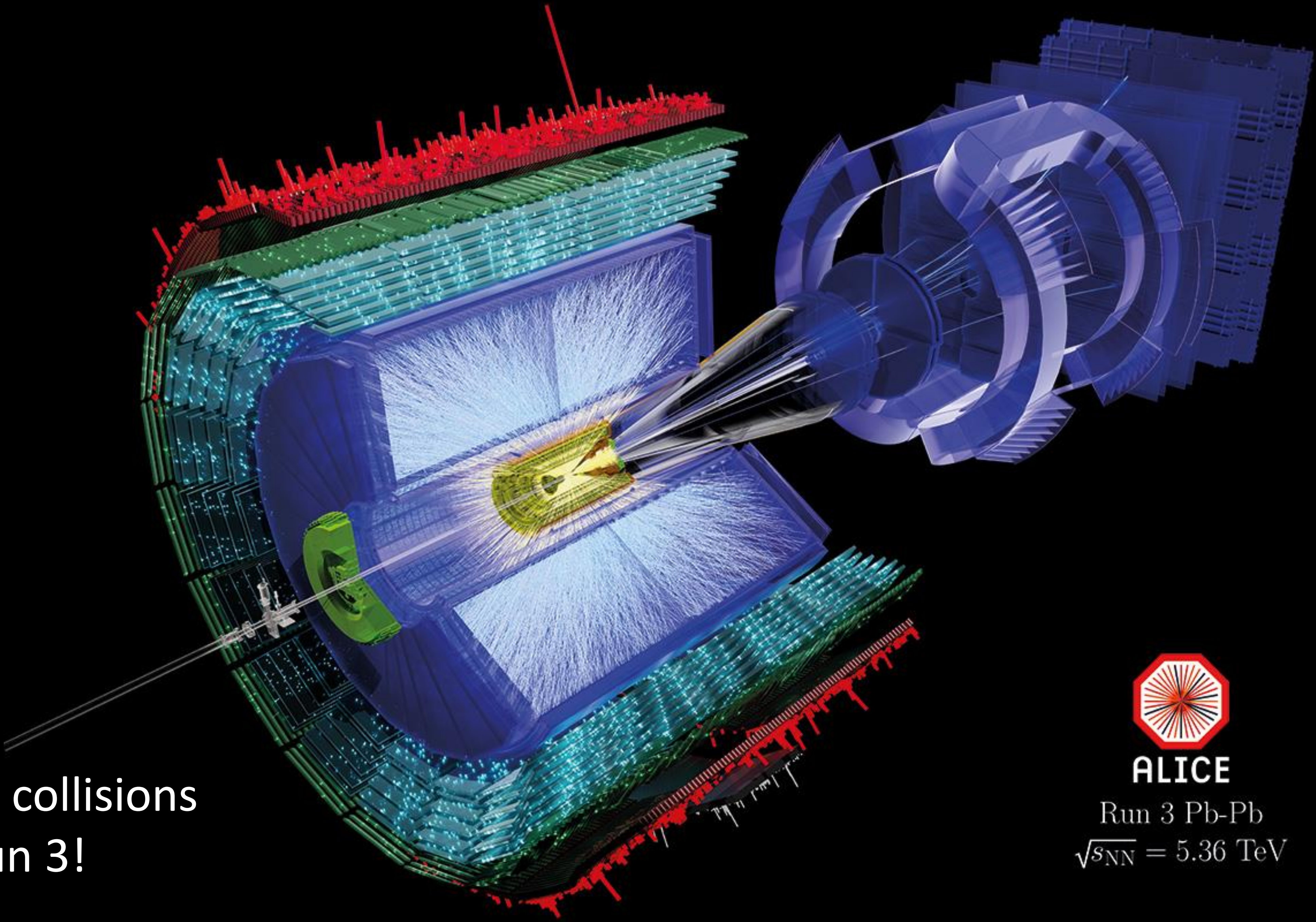


x100 more statistics for charm measurements



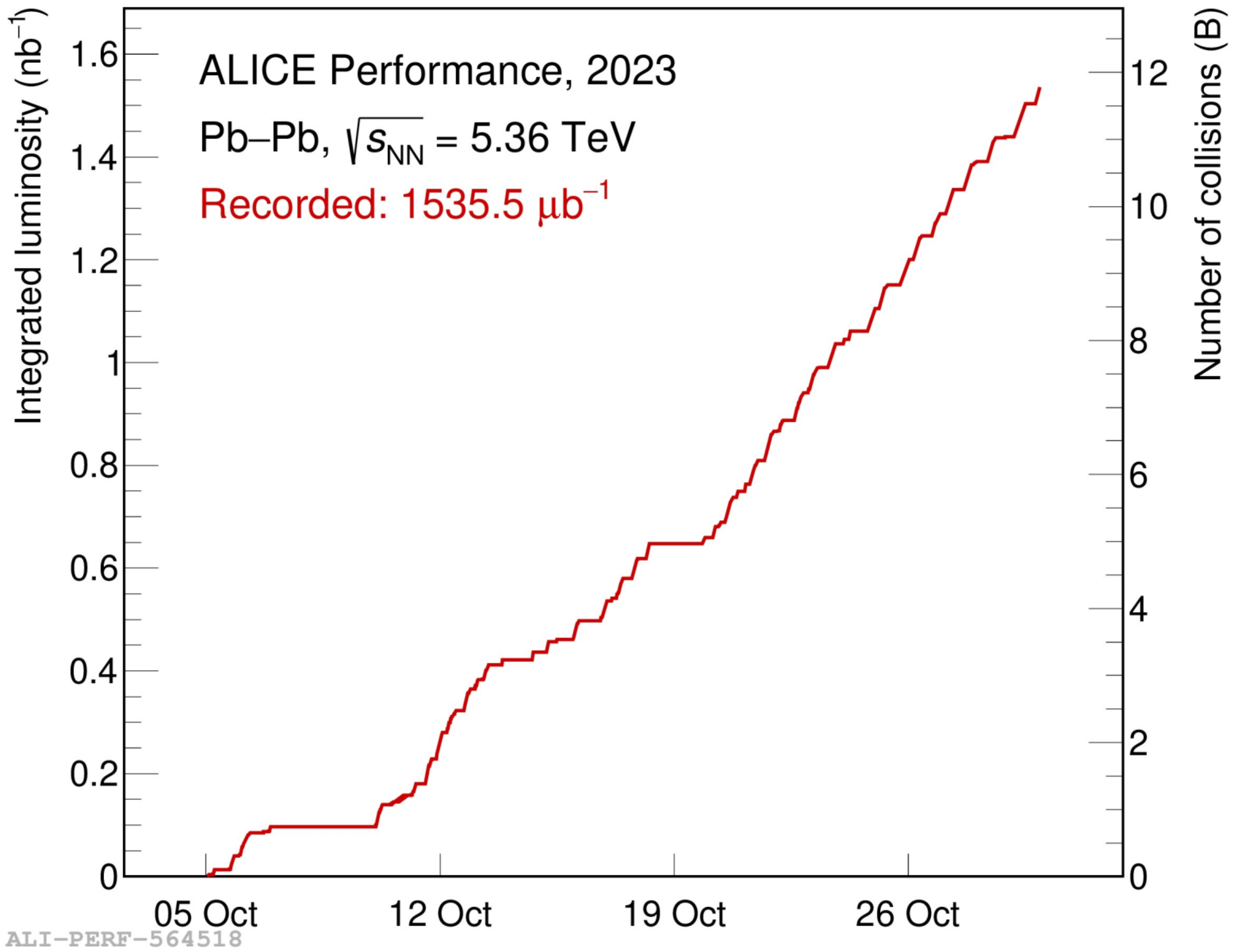
First signal of $^4\overline{\mathrm{He}}$!





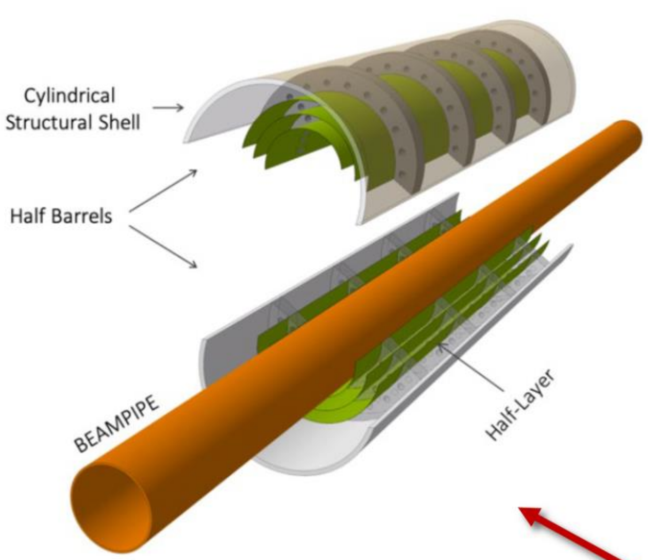
First Pb-Pb collisions
in Run 3!

ALICE performance in Run 3: Pb-Pb

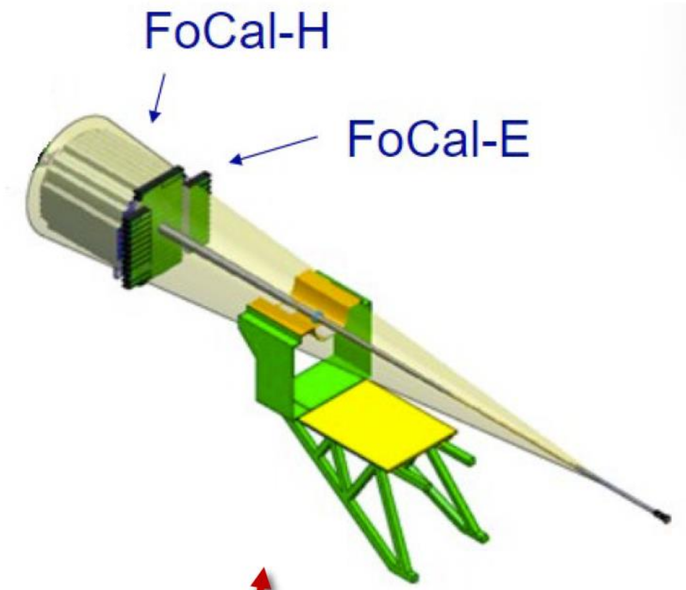


- Interaction rates up to 50 kHz. The goal reached!
- Raw data rate up to 770 GB/s
- Excellent performance and stability of all ALICE subsystems at these extreme conditions!
- **12 billion Pb-Pb collisions collected** (x40 larger minimum bias sample compared to Run 1-2)

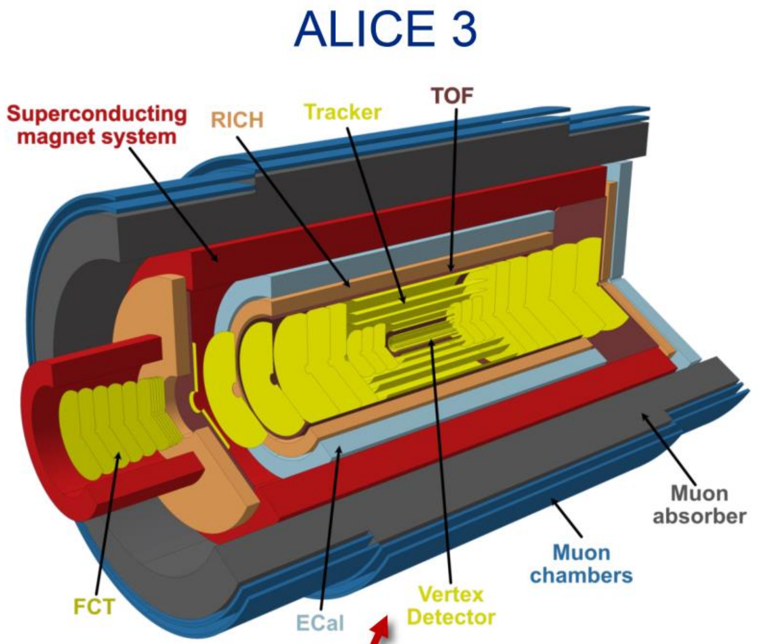
Future upgrades



ALICE, CERN-LHCC-2019-018



ALICE, CERN-LHCC-2020-009



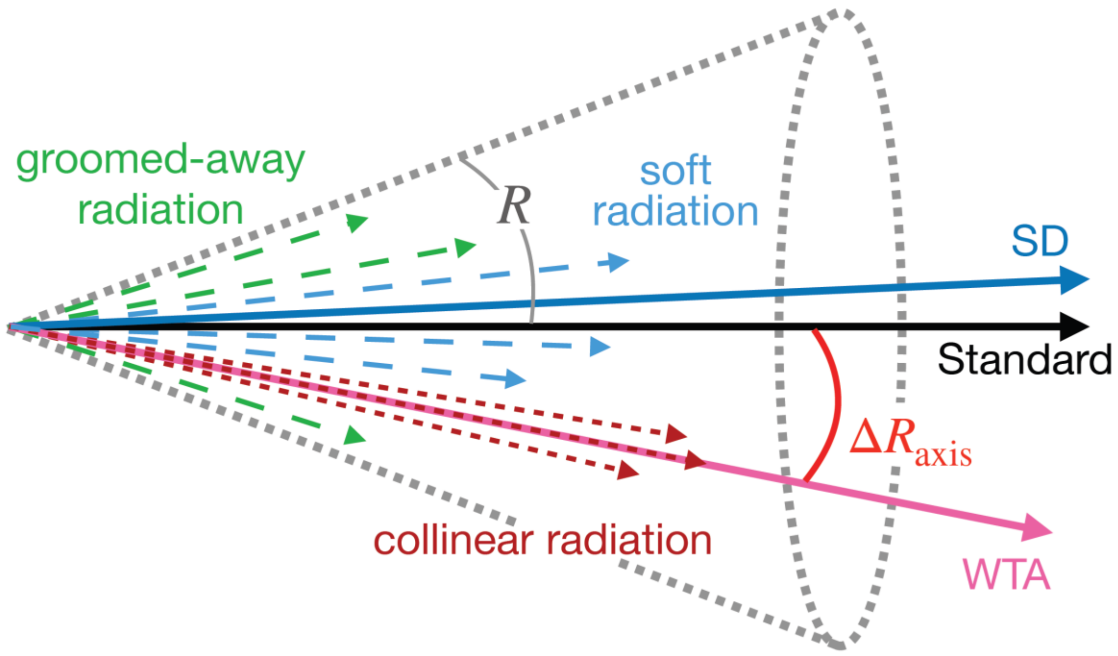
ALICE, arXiv:2211.02491

Summary

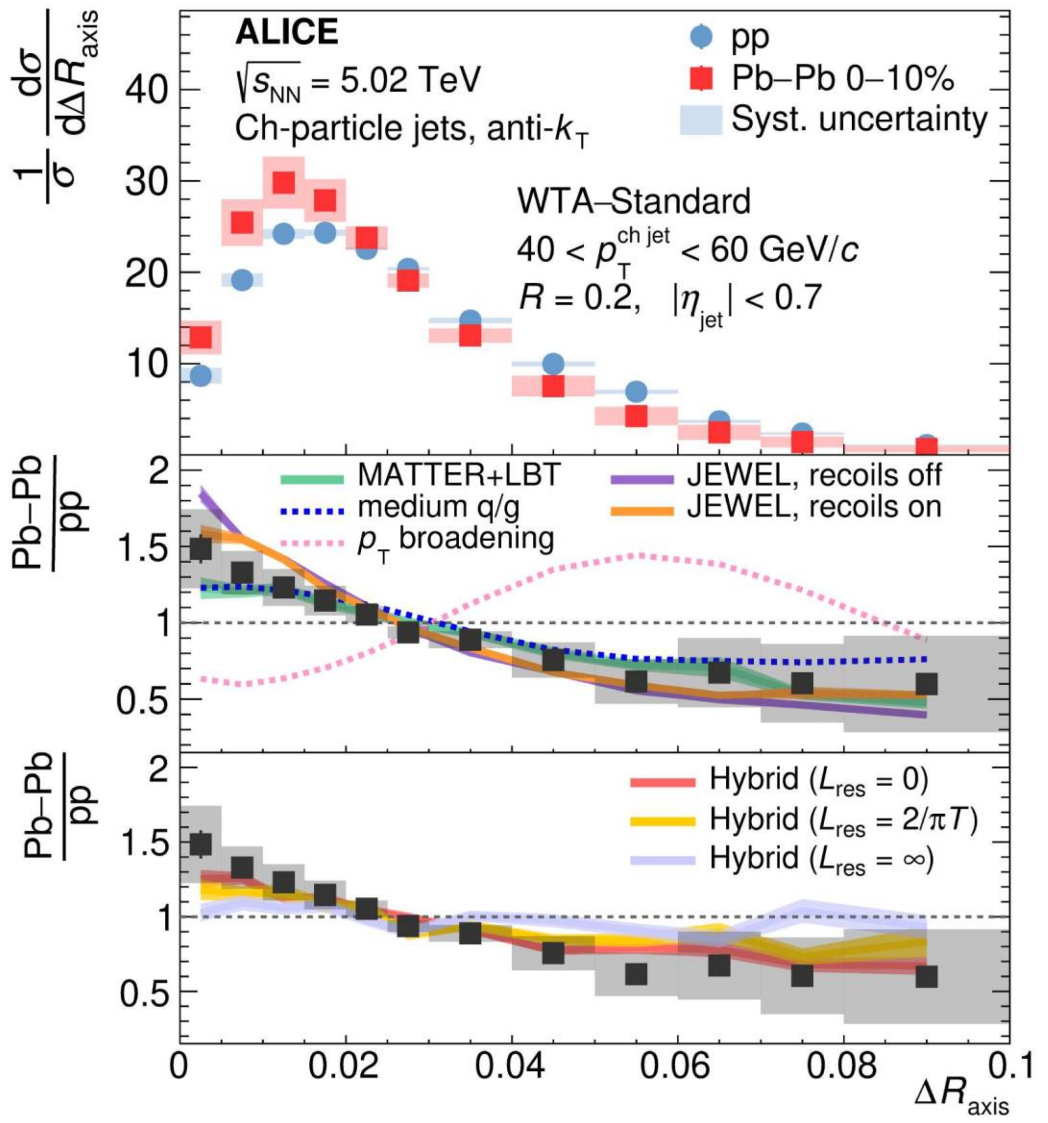
- A wealth of physics results from Run 1 and Run 2
- Providing quantitative estimates on QGP properties
- Summarized in the ALICE review paper (arXiv:2211.04384)
- Successful upgrade: excellent performance with continuous readout
- New Pb-Pb data: x40 larger minimum bias sample compared to Run 2!

BACKUP

Jet substructure studies



- ΔR_{axis} - angle between standard E-scheme jet axis and WTA axis (Winner-Takes-All, often consistent with leading particle)
- Narrowing of ΔR_{axis} distribution in Pb-Pb compared to pp
  - Quark-initiated jets more likely than gluon-initiated jets
  - Intra-jet p_T broadening disfavoured



ALICE, arXiv:2303.13347